

Monitor Points Method for Loads Recovery in Static/Dynamic Aeroelasticity Analysis with Hybrid Airframe Representation

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ABSTRACT

With the high design/performance requirements in modern aircrafts, the need for a flexible airframe structural modeling strategy during the different phases of the airframe development process becomes a paramount. Hybrid structural modeling is a technique that is used for aircraft structural representation in which several Finite Element Modeling concepts are employed to model different parts of the airframe. Among others, the Direct Matrix Input at a Grid-Point (DMIG) approach has shown superiority in developing high fidelity, yet, simplified Finite Element Models (FEM's). While the deformation approach is a common choice for loads recovery in structures represented by stick models, using structural models simulated by the DMIG representation requires the adoption of a different approach for loads recovery applications, namely, the momentum approach.

In this paper, the Monitor Points (MP) Method is introduced as an efficient methodology for loads recovery in static and dynamic Aeroelasticity analysis with hybrid airframe representation. MP method is a function provided in MSC NASTRAN that hinges on the momentum approach for loads recovery as it enables the superposition of applied loads at a user defined point and transformed into a user defined coordinate system. Here, the hybrid model is used to generate accurate predictions of the aircraft structural kinematics in flight which by its turn generates accurate profiles for the encountered aerodynamic and inertia loads. The MP method is then employed to generate high fidelity distributed loads necessary to predict the different critical load cases that generate the aircraft's loads envelop.

A sensitivity analysis is conducted which showed the high convergence of the presented methodology as it is less sensitive to modal truncation errors compared to loads recovery methods that hinge on the deformation approach.

CITATION: El Sayed, M., Gutierrez Contreras, M., and Stathopoulos, N., "Monitor Points Method for Loads Recovery in Static/Dynamic Aeroelasticity Analysis with Hybrid Airframe Representation," *SAE Int. J. Aerosp.* 6(2):2013, doi: 10.4271/2013-01-2142.

INTRODUCTION

The process of static/dynamic aeroelasticity analysis is multidisciplinary in nature [1]. It is an iterative process between the structural and the aerodynamic disciplines. Accurate predictions of the aircraft structural deformations during flight have a significant effect on its aerodynamic performance and the fidelity of the recovered aerodynamic loads.

Aerodynamic load envelops are used for the preliminary sizing of the aircraft structure. The preliminary dimensions are then used to generate the aircraft structural model.

To demonstrate the concept of the MP method, aircraft with unconventional configuration is considered for the

different analyses conducted in this paper. Different levels of structural modeling are shown in Fig. 1. A 3D FEM (Fig. (1b)) is generated once the aircraft's layout and structural details are obtained. 3D FEM is commonly used in structural design validation and optimization. Imposing a complex 3D FEM in a multidisciplinary iterative process, e.g. aeroelasticity analysis, is quite expensive. Alternatively, simplified lower fidelity FEM's of the aircraft's structure can be generated and employed [2]. The difficulty is to develop models that are sufficiently simple to be called thousands of times during the iterative process, but are sophisticated enough to accurately predict aircraft structural deformations and loads.

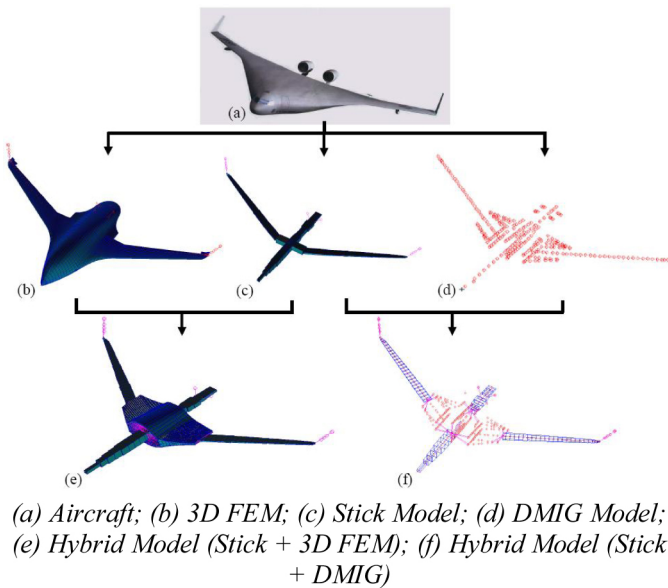


Figure 1. Different levels of structural modeling.

Simplified beam FEM's, namely, Stick models (Fig (1c)) are commonly used in aircraft industry [2, 3, 4]. The stick model development process is based on simplified beam theory [5]. The stiffness properties of the 3D FEM are extracted and condensed into a set of bar elements extending along the principal or the elastic axes of the aircraft structure. Although different shortcomings are always encountered in handling stick models, including the loss of information in the wing's chord-wise and the fuselage's span-wise directions, discontinuities in the distribution of the mass and the stiffness parameters and errors in the model performance once loaded in different load cases, however, the tolerance in the accuracy against the reduction in the computation cost redeemed them valid for the analysis of aircrafts with conventional tube and wing configurations. In these configurations the bulk dimensions of the wing and the fuselage satisfy the geometrical constraints of the simplified beam theory.

Another technique of structural models simplification is the matrix reduction methods. Matrix reduction methods are mathematical techniques that are used to reduce the size of FEM's by reducing the number of Degrees of Freedom (DOF) involved in the analysis. Different matrix reduction methods are available in literature including the Guyan reduction [6], the modal decoupling [7] and the Craig-Bampton [8] methods. It is found that the Guyan and the Modal reduction methods lack the ability of providing information of the physical distribution of the mass and stiffness parameters of the actual structure. A shortcoming that is overcome by Hashemi-Kia and Toossi [9] who developed a technique to link the dynamically reduced mass and stiffness matrices to the structural physical DOF's. On the other hand, the Craig-Bampton reduction method combines the modal DOF's with the DOF's of the boundary grids of the structure.

A matrix reduction technique is implemented in MSC NASTRAN [10] in what is called the DMIG approach (Fig (1d)). In the DMIG approach, the reduced mass and stiffness characteristics are associated to the Degrees of Freedom (DOF) of the independent nodes (aka "the A-set") of the reduced FEM. The A-set nodes are selected to provide the necessary kinematical details for each specific analysis. Two techniques can be used to generate the DMIG model. The first is based on the Guyan static reduction method where the DMIG nodes carry only the stiffness characteristics of the structure. In this case, the mass characteristics are introduced into the structural model using a lumped masses technique. The second is the Craig-Bampton dynamic reduction method. Here, the DMIG nodes carry both the mass and the stiffness characteristics of the structure.

The increase in world-wide air transport in recent years for both cargo and passengers increased the demand for the development of new, large, economically and competitive civil transport aircrafts. One way to increase competitiveness is to increase the size and payload capacity of aircrafts beyond the current limits. These limits may only be overcome by unconventional aircraft configurations. With the expected advantages of such new configurations, on the other hand, new challenges arise requiring adapted engineering solutions which cannot be derived from conventional engineering systems. For instance, alternative hybrid structural modeling techniques are adopted. Figures (1e) and (1f) show two arrangements of structural hybrid modeling as the centre portion of the aircraft is presented by either 3D FEM or DMIG representations while the rest of the aircraft is represented by a stick-model. Due to the small number of DOF's involved in the model, stick modeling is a preferable choice for structural representation specially, in iterative aeroelasticity analyses solutions. Hybrid modeling, on the other hand, enables the preservation of the model simplicity while increasing its fidelity in specific parts of the structure at which additional structural response details are required.

In the current paper, the MP method is introduced for loads recovery in static and dynamic Aeroelasticity analyses that include hybrid airframe representations. The MP method hinges on the force summation concept (momentum approach) [11, 12] for loads recovery. Here, the hybrid model is used to either retrieve more details of the structural response or as a higher fidelity structural modeling strategy that generates accurate predictions of the aircraft structural kinematics. The accurate predictions of the aircraft structural kinematics by its turn generate accurate profiles for the encountered aerodynamic and inertia loads. At that point, the MP method is employed to lump the loads and generate its distribution along the airframe load axis.

A sensitivity analysis is also conducted which showed the fast convergence of the MP method compared to loads recovery methods that hinge on the deformation approach [12, 13, 14, 15, 16, 17]. This result is in agreement with other studies available in literature [12, 16, 18].

The paper is organized in six sections. After this introduction, the fidelity of different levels of structural modeling is tested in section 2. Section 3 describes the MP method. The accuracy of loads recovered from different structural models using the MP method is presented in section 4. Section 5 on the other hand, presents a sensitivity analysis to determine the convergence of the MP method by testing its sensitivity to modal truncation errors. The paper is concluded in section 6.

FIDELITY OF DIFFERENT LEVELS OF STRUCTURAL MODELING

In this section, the fidelity of different levels of structural modeling is tested by comparing the modal characteristics of four different models for the main airframe of a generic aircraft. The four models include a 3D FEM, a stick model, a full DMIG model and a hybrid model, as shown, respectively, in Figs (1b), (1c), (1d) and (1f). In the hybrid model, the center portion of the aircraft is represented by the DMIG approach and the rest of the airframe is modeled by the traditional stick modeling method.

Before proceeding with the comparison, we review in the next sub-section the main matrix reduction methods available in literature.

Matrix Reduction Methods

Three methods of matrix reduction are reviewed, namely, Guyan, Modal Decoupling and Craig-Bampton methods.

To illustrate the concept of matrix reduction, consider the equation of motion of a FEM of order N as:

$$\mathbf{M}\ddot{\mathbf{r}} + \mathbf{K}\mathbf{r} = \mathbf{R} \quad (1)$$

where $\mathbf{M} \in R^{N \times N}$ and $\mathbf{K} \in R^{N \times N}$ are, respectively, the mass and the stiffness matrices of the FEM, $\mathbf{r} \in R^{N \times 1}$ and $\mathbf{R} \in R^{N \times 1}$ are, respectively, the nodal deformations and applied forces vectors. Damping terms are ignored.

In the Guyan reduction method, the displacement vector is split into master DOF's $\mathbf{r}_m \in R^{N_m \times 1}$ and slave DOF's $\mathbf{r}_s \in R^{N_s \times 1}$. The master DOF's are those DOF's associated with the A-set nodes of the FEM which are retained after applying the matrix reduction method. As the Guyan method hinges on a static reduction technique, then, the static part of equation (1) can be rewritten as:

$$\begin{bmatrix} \mathbf{K}_{mm} & \mathbf{K}_{ms} \\ \mathbf{K}_{sm} & \mathbf{K}_{ss} \end{bmatrix} \begin{bmatrix} \mathbf{r}_m \\ \mathbf{r}_s \end{bmatrix} = \begin{bmatrix} \mathbf{R}_m \\ \mathbf{R}_s \end{bmatrix} \quad (2)$$

From eqn (2), the slave DOF's can be expressed in terms of the master DOF's as:

$$\mathbf{r}_s = -\mathbf{K}_{ss}^{-1} \mathbf{K}_{sm} \mathbf{r}_m = \mathbf{T}_s \mathbf{r}_m \quad (3)$$

The Guyan reduction transformation equation is then given as:

$$\begin{bmatrix} \mathbf{r}_m \\ \mathbf{r}_s \end{bmatrix} = \begin{bmatrix} \mathbf{I} \\ \mathbf{T}_s \end{bmatrix} \mathbf{r}_m = \mathbf{T} \mathbf{r}_m \quad (4)$$

where $\mathbf{T}$ and $\mathbf{T}_s$ are the Guyan reduction transformation matrices; $\mathbf{I}$ is the identity matrix.

DMIG models generated by the Guyan reduction method are only efficient in static analysis. Involving such models in a dynamic analysis requires other strategies for mass representation.

The modal decoupling transformation equation is expressed as:

$$\mathbf{r} = \Phi \mathbf{q} \quad (5)$$

where Φ is a modal matrix that is constructed by concatenating the Mode shapes of the structure into its columns; $\mathbf{q}$ is the modal DOF's. In this method, the physical DOF's of the structure are reduced by expressing them in terms of the modal DOF's.

The Craig-Bampton method combines DOF's of the boundary points of the physical structure with the structural normal modes. The transformation equation of the Craig-Bampton method can be expressed as:

$$\mathbf{r} = \Phi_{CB} \mathbf{r}_{CB} \quad (6)$$

where Φ_{CB} and $\mathbf{r}_{CB}$ are, respectively, the Craig-Bampton transformation matrix and DOF's. Craig-Bampton DOF's are a combination of the modal DOF's and the DOF's of the physical boundary points of the structure.

DMIG models generated by the Craig-Bampton reduction method are efficient for both static and dynamic types of analysis.

Comparison of Modal Characteristics of Different Structural Models

The modal analysis solution in MSC NASTRAN [10], solution 103, is used to recover the modal characteristics of the four models of the main airframe of the generic aircraft. The natural frequencies of their corresponding flexible modes