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Recent Progress in Aerodynamics for Aeroelastic Analysis

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***Abstract:** Aerodynamics has gained considerable popularity in the aerospace industry. Based on the characteristics of a structure, aerodynamic behavior varies from structure to structure. A reliable aeroelastic analysis requires accurate capture of aerodynamic forces. To produce accurate aerodynamic loads, it is necessary to develop an appropriate aerodynamic model. A review of various approaches to aerodynamic modeling for aeroelastic analysis of diverse wing configurations is presented in this paper. The study covers a wide range of finite element software platforms used in the aeroelastic analysis in various flow regimes.*
***Keywords:** Aerodynamics, Aeroelastic Analysis, Finite Element, Wing Configuration, Flow Regimes*

I. INTRODUCTION

Fluid-structure interactions is an inevitable concern in the design of the various structure. In space structures, aerodynamic-structural interaction (Aeroelasticity) has become an integral part of any aircraft design. Aeroelastic phenomena usually appear in many engineering fields including aeronautical, mechanical, civil, and electrical, for example, structural engineering when studying the wind effects on the bridges and skyscrapers, etc. The design of aircraft is intended to avoid aeroelastic failures such as divergence and control reversal, and there is a requirement to avoid critical dynamic instabilities such as utter. Modern aircraft are increasingly designed to be highly maneuverable to achieve high performance. With the increasing pursuit to achieve lower weight and energy efficiency, the aircraft is made with lightweight composite materials. Aeroelastic problems arise in the airplane structure because of its lightweight and flexible surface properties as well as the large aerodynamic loads acting on it. Although research has focused on aerospace applications, more recent research efforts have involved wind energy, fluid-structure interactions, etc.

An aeroelastic analysis is carried out by coupling a structural dynamics model and an aerodynamic model [1]. The aeroelastic problems are of two types, dynamic aeroelasticity problems, and static aeroelasticity problems. Recently, a large number of research scholars have studied the problem of static and dynamic aeroelasticity problems in various structures [1-11]. In this paper, the author will discuss the various methods to develop an efficient aerodynamic model for static aeroelastic analysis. The aerodynamic data include stability and control derivatives, trim conditions, and pressures and forces.

The slender wings are subjected to appreciable structural flexibility and may undergo large deformation. Issue of geometric nonlinear may occur when the wings undergo large deformation. Traditional linear aeroelastic theories are based on the infinitesimal deformation assumption that fails to accurately analyze such deformation and the aeroelastic characteristics of flexible aircraft undergoing such a structural deformation [9]. Different wing configurations are reviewed in this paper.

The finite element (displacement) approach is the most widely used method for static and dynamic theoretical modeling of aircraft structures, providing the basic equations involving mass and stiffness terms for both aeroelastic and loads calculations. The concept behind the finite element method is to divide the geometric structure into finite elements connected at discrete points on the elements called nodes. The displacements at the nodes are the unknowns for which the equations of motion are formulated, so the continuum structure is reduced to a discretized one with a finite degree of freedom. A general finite element analysis can be broken down into three principal steps. They are pre-processing, analysis, and post-processing. The pre-processing process begins with creating a geometric model, developing a finite element model, giving these elements the correct properties, setting the boundary conditions and loading conditions, and finally, assembling these elements into a connected structure for analysis. During the analysis stage, all unknown degrees of freedom, reactions, and stresses are solved. In the post-processing stage, the results are evaluated and displayed. During the post-processing step, the accuracy of these results is hypothesized. The pre-processing stage of aeroelastic analysis is the development of the models, structural model as well as aerodynamic model. The development of the aerodynamic model is relatively difficult because it needs to account for the aerodynamic force gradients and curvature of the structure appropriately. A good aerodynamic model always yields accurate and reliable results for the analysis. Various finite element platforms are used in the modeling and analysis of aeroelastic problems. A detailed discussion of MSC/NASTRAN and elsA software is also included in this paper. This paper discusses various methods of developing aerodynamic models or programs.

II. AERODYNAMIC FINITE ELEMENT MODELING

Finite elements have shapes that are relatively easy to formulate complex geometry and analyze. The three basic types of finite elements are beams, plates, and solids. 1D beam elements are used to model long, slender flat structural members. 2D plate elements are used to model thin structural members such as aircraft fuselage skin or car body. The piston head is modeled using 3D solid elements. For example, CQUAD4 and CTRIA3 elements are some of the surface elements used to represent the individual surface components of the wing segment such as skin and web in MSC/PATRAN software [8]. MSC/ PATRAN, ABAQUS, Ansys, and elsA are some of the finite element platforms used to formulate a model for static aeroelastic analysis [6,8]. MSC/NASTRAN will be the post-processor of the aeroelastic analysis in most of the studies conducted [1,6]. Sometimes, to solve the flow-solid-thermal coupling problem of vehicle numerical simulation are more preferred, then ABAQUS software can be used to calculate the structure heat transfer and structure response. The FLUENT software can be used to calculate the aerodynamic characteristics of the aircraft [7]. The theoretical background of the MSC/NASTRAN and elsA software is discussed in detail in this paper.

A. Theories Supporting MSC/NASTRAN

The MSC/NASTRAN can support one subsonic and three supersonic lifting surface theories, as well as Strip Theory under certain conditions. Under subsonic conditions, the Doublet-Lattice method (DLM) is used, which is capable of accounting for interference between multiple lifting surfaces and bodies. The Mach Box method, Piston Theory, and the ZONA51 method are supersonic theories. MSC/Nastran also provides an automated interpolation procedure that relates the aerodynamic degrees of freedom to the structural degrees of freedom. Under subsonic conditions, the Vortex-Lattice aerodynamic theory is used, i.e., the steady case of the Doublet-Lattice method, while at supersonic speeds, the ZONA51 aerodynamic theory is utilized at zero reduced frequency.

B. Theories Supporting elsA Software

One developed the elsA software, which deals primarily with internal and external aerodynamics under low subsonic and high supersonic flow regimes [12,13]. A wide range of turbulence models is implemented in elsA for Reynolds Averaged Navier-Stokes, from eddy viscosity to the full Differential Reynolds Stress Model [12]. Elsa offers high flexibility and advanced techniques involving multi-block structured meshes, such as patched grid and overset, to handle complex configurations. Finite-volume methods are used to solve the flow equations. Upwind or cantered schemes are commonly used for space discretization. LU relaxation methods are used to solve implicit schemes for the integration of semi-discrete equations. The convergence of steady flows is improved by the use of multi-grid techniques [12].

III. VARIOUS APPROACHES IN AEROELASTIC ANALYSIS

MSC/NASTRAN aeroelastic analysis is based upon a finite element approach. Strips or boxes with aerodynamic forces are called finite aerodynamic elements. Even for complex vehicles, the aerodynamic elements must be in regular arrays. In particular, the aerodynamic elements for the lattice methods are arrays of trapezoidal boxes with sides that are parallel to the airflow. Aerodynamic elements can be designated by defining the properties of the array (panel). Advantages of linear panel methods include quick run times, relatively easy geometrical modeling, and little user interface [10].

The major limitation of linear aerodynamic methods lies in their inability to predict transonic flow fields that involve nonlinear phenomena such as shock waves and boundary layer separation. Linear aerodynamic tools are also truly restrained in modeling complicated geometries. The usage of linear panel strategies in plane structural design would possibly bring about a structure that is insufficient when subjected to the actual flight loads and often requires significant structural redesign at a later stage of the design process [10].

In the aeroelastic analysis of the generic configuration wing, an alternative aerodynamic code, Wings3D was used to generate the aerodynamic properties in the low supersonic range. The results obtained by Wing3D match well with those obtained by the doublet-lattice method in the subsonic range [1]. The Wing3D computer code incorporates thickness effects and second-order pressure rules in the design mode. Mainly Wing3D computer code was used to understand a linear potential flow about a thin wing [6]. A comparative study between the doublet-lattice method and the Wing3D program results shows that total lift is almost the same between the two methods but the maximum deflection has more variation. The rolling moment coefficients are relatively small and have a slight variation in results.[1]

MSC/NASTRAN uses an aerodynamic influence coefficient matrix generated based on the doublet-lattice method to calculate aerodynamic quantities in subsonic flow [3]. By the means of DMAP variation, a portion of the subsonic static aeroelastic analysis scheme was modified.

The Mach box method installed in the NASTRAN program helps to evaluate aerodynamic forces in supersonic flow. This method is applicable only for a symmetric configuration in NASTRAN [4]. The other option available for supersonic aerodynamics is the piston theory [5], which is valid in the range of Mach numbers from about 2.5 to 7.0.

MSC/ NASTRAN works with various linearized aerodynamics techniques to cover steady and unsteady aeroelastic analyses in the subsonic as well as the supersonic speed regime. Unfortunately, the Mach box aerodynamics module for supersonic flow regime is enforced to work only with symmetric configuration aircraft, and no aerodynamics module accounts for the leading-edge suction forces because such forces nullify each other for traditional symmetric aircraft configurations. Due to the asymmetric nature of oblique wings, they pose several technical challenges, including a high level of cross-coupling in control and dynamics, which is not present in symmetric aircraft. [6]. Available analysis programs are limited to symmetric configurations of wings, so they cannot be applied to asymmetric configurations in the subsonic range. The supersonic doublet-lattice module of MSC/NASTRAN can be used together with the external program's aerodynamic influence coefficient matrices to calculate the effects of oblique wing configurations, taking advantage of its extensive analysis and data management capabilities [6].

Also, the modified method can apply to subsonic and the supersonic range for both symmetric and asymmetric configurations. Analyzing and designing the oblique wing required the use of a three-dimensional aerodynamic model, which included a camber. The leading-edge suction force distribution at skewed positions will require further research [1].

When large deformations exist, the traditional linear method of static aeroelastic analysis yields unrealistic results. It is possible to calculate the non-planar aerodynamics of flexible wings that have large deformations using a non-planar vortex lattice method. Nonlinear structural static analysis is conducted using the finite element method. Nonlinear structural geometric problems are solved via incremental finite element methods using Lagrange formulation (ULF). Airfoil camber and wing spanwise bending are taken into account by the non-planar vortex lattice method. Here, non-planar aerodynamics is calculated using the non-planar vortex lattice method, which is efficient and does not require additional parameter adjustments. An acceptable analysis accuracy could be obtained using the nonlinear method using the finite element method and the nonplanar vortex method [9].

IV. CFD-BASED AEROELASTIC ANALYSIS

Although recent improvements in Computer Fluid Dynamics techniques have been very promising, wind tunnels have proven to be the most reliable way to estimate the effects of wind on structures experiencing aeroelastic phenomena. Currently, high-fidelity CFD tools are available to aircraft designers and are commonly used to design aerodynamic configurations. CFD codes of variable fidelity can accurately predict flow fields about complex aircraft configurations in various flow fields, thus improving the accuracy of linear tools. In contrast to linear aerodynamics, CFD tools require long run times, complex geometrical modeling, and mesh generation in comparison to linear aerodynamics tools. They require a higher level of proficiency from the user when it comes to setting up run parameters and interpreting the results [10].

The literature describes two approaches, CFD-based unsteady aeroelastic analyses, and transonic aeroelastic instabilities prediction. In direct transient-response analysis, aeroelastic simulations are time-stepped by coupling CFD and structural dynamics. Instabilities are predicted by analyzing each transient for decaying or diverging responses. For unsteady aerodynamics, an indirect approach seeks reduced-order models (ROMs). ROMs can then be coupled with structural dynamics for transient response simulations, or they can be used in stability analyses [10].

A CFD-CSD coupled analysis of a high AR wing is conducted to verify its static and dynamic instability. CFX and Ansys were used to perform Aerodynamic analysis and structural analysis respectively. This method involves using the CFD results as the load condition for structural analysis, then using the displacement result for CFD analysis. In both static and dynamic situations, the present wing is aeroelastically stable [14].

A parallel CFD-CSD simulation program has been developed for analyzing static aeroelasticity. For time-accurate computations of unsteady flows, the CFD algorithm is used in conjunction with a structure's solver and deforming mesh algorithm [11]. A generic wing was studied using both Euler and Navier-Stokes computations. Computational cost and time for obtaining a static aeroelastic solution are practically the same as for a rigid body. It is important to note that rigid wing and flexible wing solutions, as well as Euler and Navier-Stokes solutions, differ significantly. For accurate predictions of wing aerodynamic performance, static aeroelastic calculations should be performed instead of rigid wing calculations [11].

The process of extrapolating displacement fields of substructural finite element models to the SFI is imperative not only for producing a continuous displacement field at the SFI but also for generating a nodal force vector consistent with the pressures applied at the SFI.

To estimate displacements outside the modeled elements, one must resort to assumed displacement extrapolation functions. The purpose of this approach is to provide a practical means of enforcing both displacement continuity and energy conservation across the multidisciplinary interface [15].

V. CONCLUSIONS

The paper reviewed some of the recent approaches in the development of aerodynamics in aeroelastic analysis. A wide range of aerodynamic methods, including linear, non-linear, and non-planar, were discussed in this paper. This paper shows that CFD-based aeroelastic tools can accurately predict aeroelastic effects in various applications. In a wide range of flow regimes, CFD-based tools are capable of evaluating aeroelastic problems with great accuracy and reliability. But CFD tools require long run time, complex geometric modeling, and mesh generation in comparison to linear aerodynamics tools.

In the preceding sections, recent progress in the development of an aerodynamic model for aeroelastic analysis for symmetric and unsymmetric wing configurations was discussed. The use of static aeroelastic calculations instead of rigid wing calculations can provide more accurate predictions of wing aerodynamic performance. Additionally, MSC/NASTRAN and MSC/PATRAN are the most commonly used pre-processors and post-processors in various aerospace industries.

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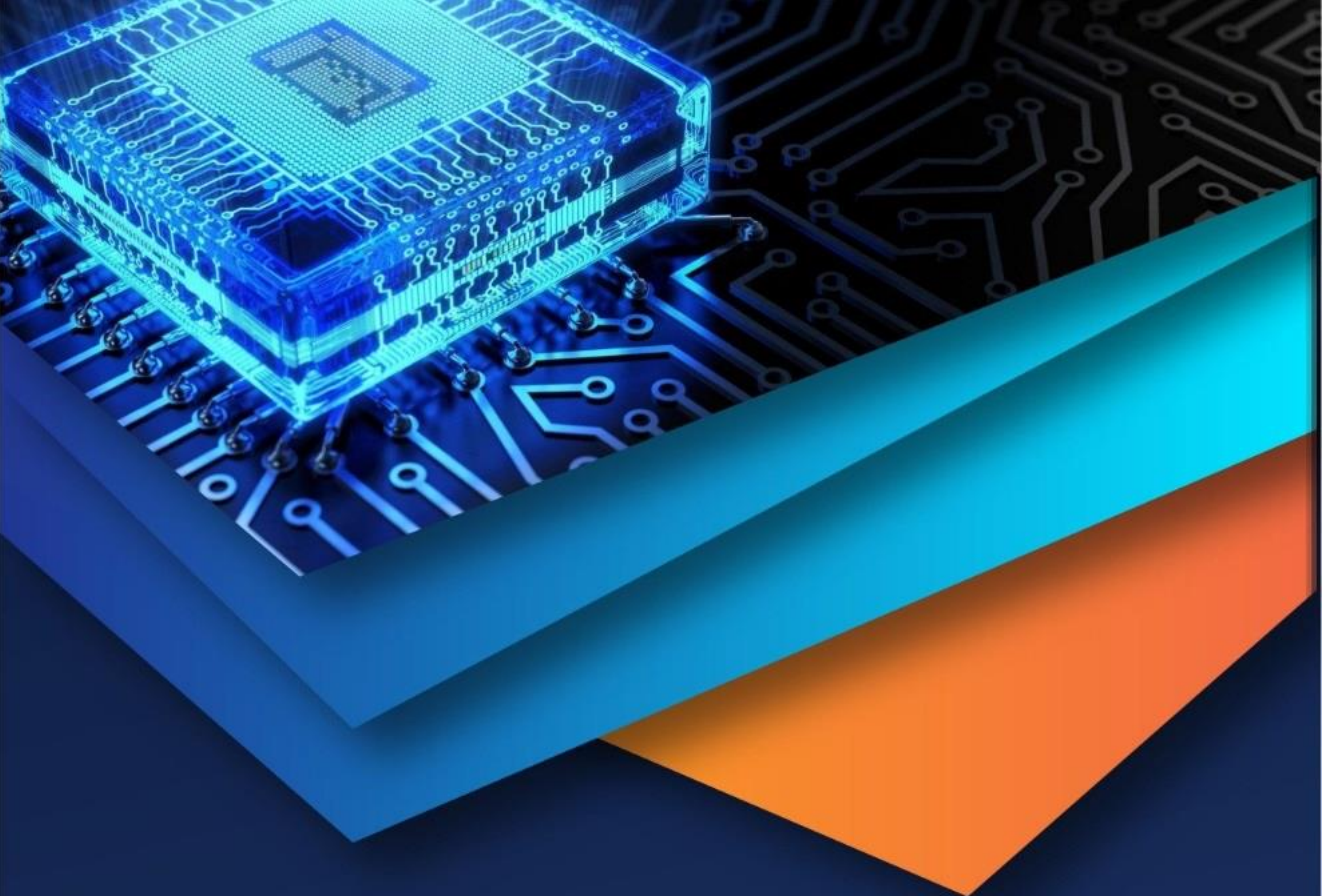

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