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Abstract

In the last decades, the development of composite materials in the aerospace sector has broadened the structural design space, especially with respect to complex problems involving fluid-structure interactions (FSIs) and non-linear aerodynamic phenomena. The full exploitation of the potential offered by composite materials in such applications is critically related to the capability of modelling the involved interactions with suitable fidelity, which is based on the development of reliable structural and aerodynamic models and their consistent coupling. In this work, the combination of the Carrera Unified Formulation (CUF) and Finite Element Analysis (FEA) is adopted to model composite laminates under aerodynamic loading and the structural model is coupled with high-fidelity CFD tools offering the possibility of selecting a variety of different aerodynamic theories. A case study is presented, in which the open source software SU2 is used to solve the Navier-Stokes three-dimensional equations, thus overcoming contingent limitations of low-fidelity aerodynamic analyses. Few preliminary numerical results are presented and discussed to illustrate the potential of the framework being developed.

Key words: *Aeroelasticity; Carrera Unified Formulation; SU2; Composite materials*

1 Introduction

Aeroelasticity plays a crucial role in aerospace engineering, as it helps to predict and prevent static or dynamic behaviour of structural components operating under the action of aerodynamic loads, helping to predict and prevent the occurrence of dangerous or even catastrophic events. An important class of aeroelastic problems aims at investigating the behaviour of structural components under the action of steady aerodynamic forces, with the objective of assessing the effects of structural deformations on the aerodynamic loads redistribution and identifying potential aeroelastic divergence conditions. The analysis of fluid-structure interactions is built on the coupling of structural and aerodynamic models, based on the construction of reliable algorithms to pass the information from the structural to the aerodynamic level (e.g. updated impermeable wall conditions) and viceversa (e.g. updated pressure distribution and loads).
Composite materials are today widely employed in aerospace structures and the width of their design space is largely exploited in terms of aeroelastic tailoring, especially throug use of suitable computational mechanics tools. Recently, the Carrera Unified Formulation (CUF) [1] has emerged as a powerful method to investigate the behaviour of general composite configurations, offering large flexibility in the order of the adopted structural theories.
In the literature, CUF is generally coupled with low-fidelity aerodynamic models, yet able to provide accurate estimates in certain operational conditions. In this work, the coupling of CUF with high-fidelity CFD is proposed, to extend its use to the analysis of a broader class of aeroelastic problems; in particular, the open-source software SU2 [2] is employed for CFD analysis.
The manuscript is organised as follows: a brief problem description is first provided, along with a brief theoretical background for structural and aerodynamic analysis; preliminary numerical results are then discussed to illustrate the potential of the tool being developed; eventually, a few conclusions about future directions are given.

2 Problem description

Beam structural theories are often adopted for investigating the aeroelastic behaviour of slender bodies. However, such structural approximation may be inadequate when low aspect-ratio lifting surfaces, e.g. tail surfaces, are considered. In this work, plate structural theories are considered and developed for aeroelastic analysis of lower-to-higher aspect-ratio components.
The structural theories are formulated in the framework of the CUF, which offers a general formalism and flexibility in terms of the underlying adopted structural theory. Advanced CFD can be avoided when simple aerodynamic conditions are considered; however it becomes essential when the flow conditions become inconsistent with simpler vortex/doublet lattice modelling. The objective of this work is then the development of a computational tool coupling a flexible structural computational framework with a flexible CFD framework.
In the literature, much research has been devoted to the analysis of plates aeroelasticity ([3], [4]), often considering composites as the main candidate for aeroelastic tailoring and structural sizing. Different kinds of composite structures have been modelled employing CUF and FEM, see e.g. [5] and [6], adopting either Equivalent Single Layer (ESL) or Layer Wise (LW) approaches.
CUF is based on general kinematic assumptions, which can be expressed as

$$u_k(x_1, x_2, x_3) = \sum_{n=0}^{N} F_n(x_3) u_{kn}(x_1, x_2), \qquad k = 1, 2, 3, \tag{1}$$

where (x_1, x_2) identify the in-plane coordinates, x_3 is the through-the-thickness coordinate, F_n denotes through-the-thickness expansion functions, whose specific form may vary, and N is the adopted order of expansion. In this work a Taylor-like expansion is adopted along the thickness direction. After the discretisation of the analysed domain into non-overlapping finite elements, Eq.(2) is coupled with a suitable representation of the in-plane functions, over individual elements, in terms of nodal values $\tilde{u}^i$ and linear shape functions $N_i(x_1, x_2)$, as customary in FE formulations, which then produces a CUF-FEM kinematic model as

$$u_k(x_1, x_2, x_3) = \sum_{n=0}^{N} F_n(x_3) \sum_{i=1}^{N_n} N_i(x_1, x_2) \tilde{u}^i_{kn}, \qquad k = 1, 2, 3, \tag{2}$$

where N_n is the number of nodes adopted for the considered element.
The previous generalised kinematical model can be used in the statement of the Principle of Virtual Displacements (PVD), thus providing the standard FEM matrices (stiffness, mass, damping). Using the CUF formalism, the entries to such matrices can be expressed in terms of *fundamental nuclei* [1], which are independent from the order of expansion and the nodal coordinates. The loading vectors entering the formulation can be computed accordingly. The entries A^{ij}_{mnkl} of the fundamental nucleus and the components P^j_{lm} of the loading vectors are defined by

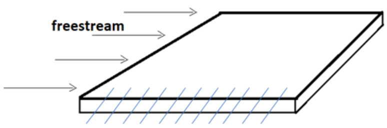
$$\delta L_{int} = \delta \tilde{u}^i_{kn} A^{ij}_{klnm} \tilde{u}^j_{lm}, \qquad \delta L_{ext} = \delta \tilde{u}^j_{lm} P^j_{lm} \tag{3}$$

and can be computed using the kinematic assumptions in Eq.(2) in the PVD.
Once the structural matrices are obtained, the open-source software SU2 has been employed for the CFD analysis, because of its efficiency and simplicity of input. In this work stationary Navier Stokes equations are employed for the analysis of the aerodynamic flow around the section wing presented in Ref.[7]. The finite volume method is applied on the discretised control volume, and the final system is linearly solved through a Flexible Generalised Minimum Residual solver. The density of dry air is assumed as $\rho = 1.225\,\mathrm{kg/m^3}$ and the dynamic viscosity $\mu = 1.789\,\mathrm{kg/ms}$. SU2

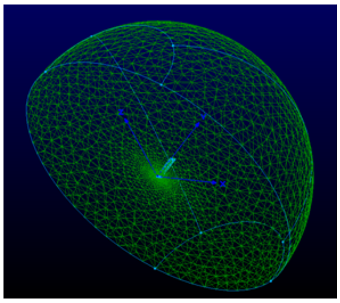
computes pressure values for the nodes of the CFD surface mesh on the wing. Pressure values provided by SU2 are converted into forces over the FE structural mesh through an interpolation matrix based on the Moving Least Square Technique.
At this stage, the correct transfer of aerodynamic forces from SU2 to the structural mesh, at different airspeeds, is validated considering the wing tip displacements and comparing the computed values with the results obtained through `NASTRAN sol 144` in Ref.[7].

3 Numerical results

Before coupling the structural and the aerodynamic codes, the CUF-based structural model has been validated. The structural model allows the analysis of composite laminate plates with general boundary conditions and loading cases. The implemented code has been validated for static and frequency analyses against standard FEM results.
For the aeroelastic static analysis, a wing with rectangular planform exposed to a free-stream velocity $V = 10$, 30, 50 m/s is considered, Fig.(1 a), with an angle of attack $\alpha = 1°$. The wing has semi-span $b = 5$ m and presents rectangular transverse section with constant aerodynamic chord $c = 1$ m and thickness $t = 20$ mm. The aerodynamics is studied through an hemispheric three-dimensional control volume of radius $R = 30c$, as shown in Fig.(1b).
Table 1 reports the results in terms of wing-tip LE vertical displacements, compared to the values reported in Ref.[7]. It is emphasised that, while the aerodynamic mesh is enriched for three-dimensional CFD, the structural model already recovers accurate results at with the first order of expansion, i.e.$N = 1$ in Eq.(2). Moreover, it may be of interest to mention that, for this simple problem, the employment of a plate theory provides accurate results with a number of DoFs lower than that required by CUF based 1D-beam models, Ref.[7]. Relatively larger error can be observed at increased free-stream velocities $V = 50$ m/s, due to irregularities in the flow's behaviour because of the sharp geometry of the plate in a 3D CFD environment.



(*a*) Rectangular wing



(*b*) Three-dimensional view of the CFD control volume

Fig. 1. Geometric configuration of the rectangular wing and CFD control volume

4 Conclusions

Preliminary results obtained from aeroelastic static analysis performed through a CUF-FEM-CFD framework are presented and discussed. The aeroelastic framework couples a structural model for composite structures, based on the Carrera Unified Formulation, and the general open-source tool `SU2` for aerodynamic analysis. The presented preliminary results validate the coupling

Model	V = 10 m/s	V = 30 m/s	V = 50 m/s
EBBM - Beam, from [7]	7.6272	68.611	190.40
N = 1 - Beam, from [7]	7.6275	68.622	190.48
N = 2 - Beam, from [7]	7.0244	68.236	190.48
N = 3 - Beam, from [7]	7.4966	73.241	224.45
N = 4 - Beam, from [7]	7.5126	73.797	243.94
NASTRAN, from [7]	7.5446	73.731	245.49
N = 1 - Plate, Present	7.6149	72.093	197.28

Table 1: Vertical displacements at the tip LE [mm].

in terms of transfer of aerodynamic loads for simple geometries and boundary conditions. Further developments of the present research, along with refinement of CFD meshing, involve Equivalent Plate Modelling for airfoil-shaped wing sections and aeroelastic tailoring studies to observe the influence of fibre orientations, stacking sequences and other composite materials factors.

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