# Development of a multi-field computational tool for high-fidelity static aeroelastic simulations

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**Abstract.** A new method for high-fidelity aeroelastic static analysis of composite laminated wings is proposed. The structural analysis and the fluid-dynamic analysis are coupled in a heterogeneous staggered process. The Finite Element Method (FEM), the Carrera Unified Formulation (CUF) and Equivalent Plate Modelling (EPM) are combined to model complex three-dimensional geometries in a bi-dimensional framework; Computational Fluid Dynamics (CFD) is employed to solve the Navier-Stokes equations and different turbulence models (i.e. Spalart-Allmaras) through SU2, an open-source software that implements C++ routines for 3D fluid-dynamics analysis. The Moving Least Square patch technique is adopted to manage the fluid-structure interaction. The use of an equivalent plate model, as opposite to 1D models often employed in the literature, shows competitive performances in terms of number of degrees of freedom. High-fidelity aerodynamics allows studying non-linear phenomena associated to irregularities of the fluid-structure interaction, showing a level of accuracy that low-fidelity methods such as Vortex Lattice Method (VLM) and Doublet Lattice Method (DLM) are unable to provide. Such advantages are balanced by the need to elaborate a staggered iterative method for the resolution of static aeroelastic problems, which leads to higher computational costs.

## Introduction

Aeroelasticity has a fundamental role in many fields of engineering. Multiple strategies are adopted in the literature to investigate the behaviour of structures subjected to the action of a fluid, so to avoid catastrophic phenomena such as divergence or flutter. Besides providing insights into potentially catastrophic phenomena, aeroelastic methods allow to investigate the aerodynamic loads redistribution due to the structural deformation, thus providing a valuable tool for the assessment of the structural performance. When composite materials are involved, Aeroelastic Tailoring aims at selecting suitable material arrangements so to provide reasonable margins with respect to dangerous operating conditions. Such tasks generally require reliable computational models for representing the aero-structural interaction.

CUF [1] provides a general framework for the generation of variable order structural theories and it has been successfully employed for the generalised analysis of composite structures. In this work, EPM [2] is combined with CUF and FEM to generate variable order structural models for aeroelastic analysis.

The fluid properties and phenomena are studied through the CFD open-source software SU2 [3], from which pressure distribution is obtained. This high-fidelity approach prevents the loss of information inherent to low fidelity theories such as VLM or DLM, especially when the drag and possible non-linearities coming from irregular geometries or high-speed regimes play important roles.

After a brief introduction to the main items of the developed framework, some representative results are reported to illustrate its scope and potential.

## Theoretical Background

In this work an EPM+CUF+FEM approach is chosen to model generally complex composite structures within a static aeroelastic context. The strategy shows to be computationally competitive with respect to classical CUF beam models employed for aeroelastic analysis. In the CUF, the kinematic model may be represented as

$$\boldsymbol{u}(\hat{\boldsymbol{x}}) = \boldsymbol{F}(\hat{x}_3)\boldsymbol{U}(\hat{x}_1, \hat{x}_2) \tag{1}$$

where $\boldsymbol{u}(\hat{\boldsymbol{x}})$ collects the displacement components at the space point $\hat{\boldsymbol{x}} = (\hat{x}_1, \hat{x}_2, \hat{x}_3)$ which spans a three-dimensional structural domain, $\boldsymbol{F}(\hat{x}_3)$ is the matrix containing through-the-thickness functions and $\boldsymbol{U}(\hat{x}_1, \hat{x}_2)$ are the generalized displacement components.

In the proposed static aeroelastic framework, the kinematic model is employed in conjunction with the Principle of Virtual Displacements (PVDs) for addressing generally complex structural components of aeronautic interest, e.g. a wing with skins or spars or ribs. The volume integration needed for computing the stiffness contributions takes into account the material distribution of the considered structure, separating through-the-thickness integration from the integration over the reference plane, thus providing an equivalent plate representation of the analysed structure.

The CFD analysis is based on Reynolds-averaged Navier-Stokes equations and turbulence models such as the Spalart-Allmaras or $k - \omega$ models. SU2 solves these equations through a discretization of the 3D domain and applying the Finite Volumes Method once the freestream conditions ($\rho_\infty$, $V_\infty$) are given. If $\breve{\boldsymbol{x}} = (\breve{x}_1, \breve{x}_2, \breve{x}_3)$ is the three-dimensional CFD domain, tractions are defined by

$$\boldsymbol{t}(\breve{\boldsymbol{x}}) = \frac{1}{2}\rho_\infty V_\infty \boldsymbol{c}(\breve{\boldsymbol{x}})\boldsymbol{n}(\breve{\boldsymbol{x}}) \tag{2}$$

where $\boldsymbol{c}(\breve{\boldsymbol{x}})$ is the vector of pressure and skin friction coefficients $c_p$, $c_{f,\breve{x}_1}$ and $c_{f,\breve{x}_2}$ and $\boldsymbol{n}(\breve{\boldsymbol{x}})$ contains the normal vectors to the surface defined as a boundary wall.

These tractions are transferred to the structural model through the Moving Least Square patch technique, which is based on the conservation of energy and minimisation of the mean square error on two displacement fields defined over the aerodynamic and structural domains, weighted by radial basis functions.

$$\sum_{k=1}^{\hat{N}} \boldsymbol{F_k}\big(\delta\hat{\boldsymbol{U}}\big)_k = \int_{\breve{\Omega}} -\boldsymbol{t}(\breve{\boldsymbol{x}}) \sum_{m=1}^{\breve{N}} S_i \sum_{k=1}^{\hat{N}} h_{ij}\big(\delta\hat{\boldsymbol{U}}\big)_m \, d\boldsymbol{A} \tag{3}$$

$$\text{Minimise} \int_{\Gamma} \chi\big(\mathrm{Tr}\big(\delta\breve{\boldsymbol{U}}\big)|_\Gamma - \mathrm{Tr}\big(\delta\hat{\boldsymbol{U}}\big)|_\Gamma\big)^2 d\boldsymbol{A} \tag{4}$$

where $\breve{N}$ and $\hat{N}$ are the number of CFD mesh nodes and structural mesh nodes respectively (with indexes $k$ and $m$), $S_i$ are base functions for the aerodynamic surface domain approximation, $h_{ij}$ is the single element of the interpolation matrix $\boldsymbol{H}$, $\chi$ is the radial basis function and $\Gamma$ is the virtual surface domains on which the traces of $\delta\breve{\boldsymbol{U}}$ and $\delta\hat{\boldsymbol{U}}$ are projected.

The staggered iterative process for static aeroelastic analysis consists of the recalculation of pressure loads for every change in the geometry of the structure caused by deformation. $\boldsymbol{H}$ is employed to transfer information from the structural to aerodynamic domain and vice versa, and it is computed once and re-used in every staggered iteration. An overall schematic representation of the method is reported in Fig.(1).

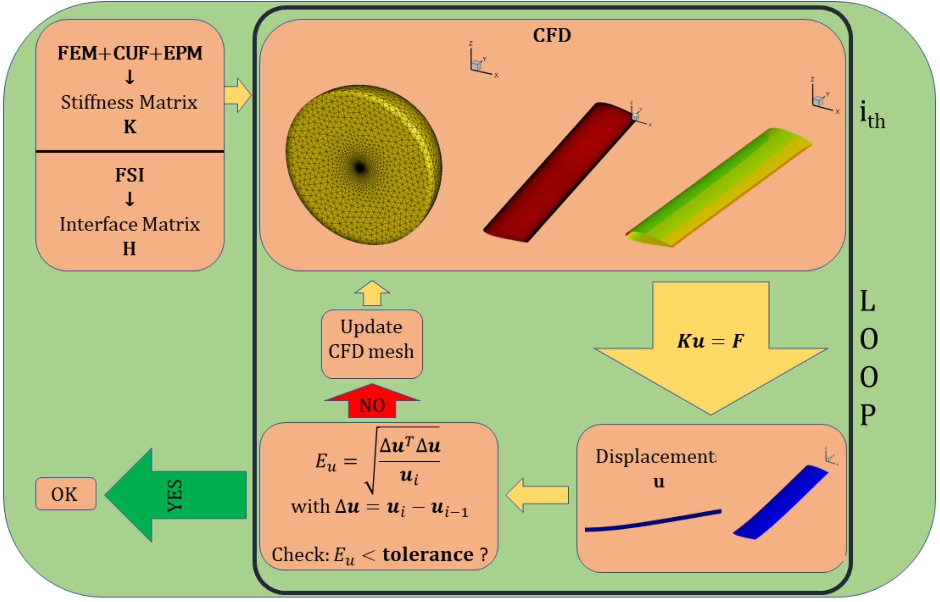

*Figure 1: Scheme of the staggered iterative static aeroelastic analysis*

## Preliminary computational results

Some preliminary results are reported here. First, the EPM is assessed in terms of accuracy considering a torsional load scheme for a realistic composite wing configuration. Second, the validation of the static aeroelastic response of an isotropic wing with a NACA2415 airfoil transverse section and two spars is shown and compared to the solutions reported in Ref.[4].

## Structural validation: torsion of a composite [0/90] laminate wing

A NACA2415 straight wing with span $b = 5$ m, chord $c = 1$ m, skin thickness of $t_{sk} = 0.04h$, being $h$ the height of the airfoil, and two spars positioned at $x_{sp1} = 0.25c$ and $x_{sp2} = 0.75c$ respectively with thickness $t_{sp1} = 0.1h$ and $t_{sp2} = 0.07h$ is considered. The wing is subjected to a torsional load applied through a suitable fictitious distribution of pressures on portions of the lower and upper sides of the wing, as shown in Fig.(2). The value of the pressure distribution is $p = 1$ Pa. The results presented in Fig.(3a-3b) show good accuracy with respect to the results obtained from ABAQUS through $\sim 10^6$ quad-structured 2D shell elements. The error $e_{\%}$ is measured on the maximum displacement, located at the leading edge of the tip section, and on the tip-section twist $\Delta u_z = u_z(0, b, 0) - u_z(c, b, 0)$.

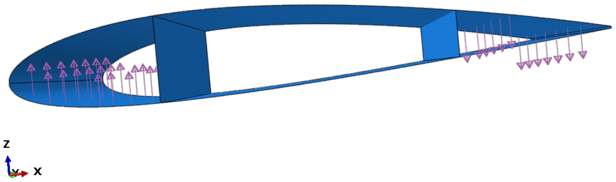

*Figure 2: Load scheme for the structural validation.*

## Aeroelastic deformation of a straight wing in subsonic conditions

The same geometry from Section 1.1 is adopted for a static aeroelastic analysis with isotropic aluminium, considering a freestream at $V_\infty = 50$ m/s in standard conditions. The result is compared with that reported in Ref.[4] and it shows a 7% difference due to the difference between the employed aerodynamic theories. In Fig.(4a-4b) the step values of $u_{z,max}$ and percentual error from the staggered iterative process are presented, with a comparison between $N_u = 1$ and $N_u = 3$, which represents the order of the expansion in the kinematic assumption.

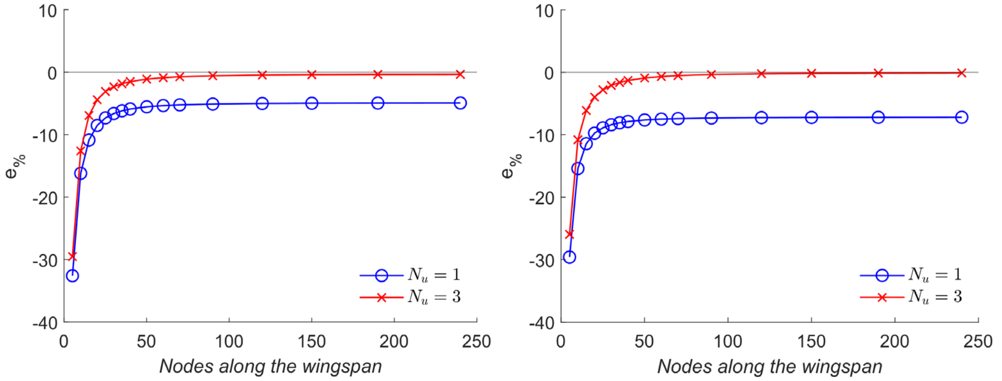

Figure 3: Results of structural validation for a torsional load on a composite wing

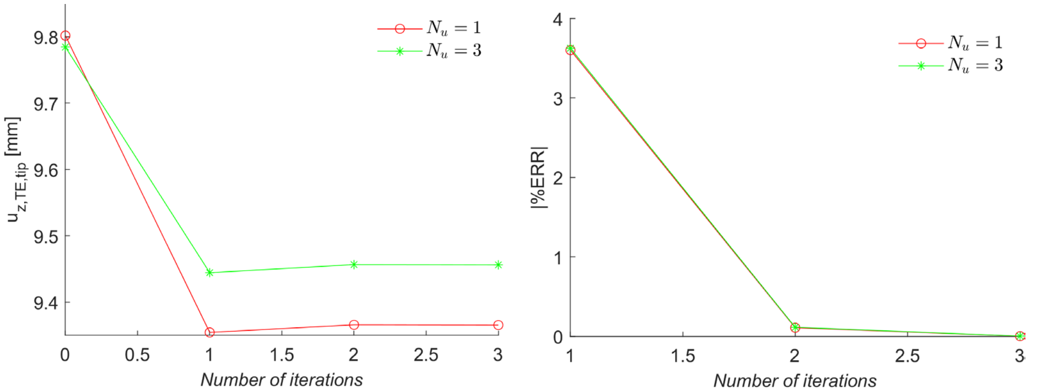

*Figure 4: Convergence of the reference analysis variable in the staggered aeroelastic solution scheme*

## Conclusions

Some preliminary results from a new CUF+FEM+EPM+CFD approach for static aeroelastic analysis are presented, showing the flexibility of the proposed tool for the analysis of complex geometries and different materials. The main advantage of the method is the accuracy in the fluid-structure coupling, which allows the study of complex aerodynamic conditions without changing anything in the structural approach.

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