Aerostructural Analysis and Optimization using Viscous-Inviscid Interaction

Paul Dechamps*, Adrien Crovato, Grigorios Dimitriadis and Vincent E. Terrapon

Aerospace and Mechanical Engineering department,

University of Liège,

Allée de la Découverte 9, 4000 Liège,

Belgium

*paul.dechamps@uliege.be

ABSTRACT

Aeroelastic analysis and gradient-based optimizations using numerical simulations are increasingly used during the preliminary stage of transonic aircraft design. Many solutions have been proposed using the Reynolds-Averaged Navier-Stokes (RANS) equations coupled with a FEM structural solver. However, the computational cost, mainly driven by the aerodynamic solver, remains prohibitive in the early design stages. The computational cost can be lowered by considering inviscid flow models based on the Euler equations or the full-potential equation. However, such models fail to capture the correct shock position, cannot predict the moment acting on the wing accurately and are not able to predict friction drag. An interesting alternative is the *Viscous-Inviscid Interaction* (VII) method, whereby an inviscid flow model is coupled with a boundary layer solver to account for viscous effects in the vicinity of the body. Many three-dimensional VII aerodynamic analyses have been presented and have been shown to provide physical results, at a fraction of the cost of RANS simulations [1, 2]. However, these methods lack an analytical formulation to compute the required gradients in order to be used efficiently in a gradient-based optimization framework. This work investigates the use of a VII method in the context of aerostructural analysis and optimization and the development of the associated methodology to efficiently compute the gradients in transonic configurations. In particular, the free and open-source VII solver BLASTER [1] [2–4] has been developed for these applications. In BLASTER, the full-potential solver DART [5, 6] [2] is coupled with a pseudo-unsteady boundary layer solver using the transpiration velocity concept through a quasi-simultaneous coupling strategy. Three-dimensional solutions on finite wings are obtained using a quasi-2D strip-based approach, as presented in Dechamps *et al.* [2]. Gradients required for optimization of two-dimensional cases are computed using an adjoint methodology and the overall method has been successfully applied to airfoil aerodynamic optimization cases.

In this work, the VII method is applied to the well-documented Simple Transonic Wing (STW) benchmark model [3] presented by Gray and Martins [7]. The wing has a trapezoidal planform with no twist and a conformal composite wingbox with upper and lower skins. The high-fidelity RANS solver ADflow used by the original authors is replaced here by BLASTER. The aerodynamic

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[1] https://gitlab.uliege.be/am-dept/blaster

[2] https://gitlab.uliege.be/am-dept/dartflo

[3] https://github.com/MDOBenchmarks/MDOAeroelasticBenchmark/tree/main/STW-Files

model is coupled to the finite element (FE) library TACS [4] [8, 9], used to compute the structural part of the problem. Loads and displacements are transferred using MELD [5] [10, 11]. The multidisciplinary coupling is enabled by MPhys [6] [12], a library built on top of OpenMDAO [7][13] and the coupled system is solved using a non-linear block Gauss-Seidel (NLGBS) solver. The benchmark aeroelastic analysis is solved using the BLASTER-TACS setup in cruise conditions at $M = 0.77$ for an altitude of 10400 m. The resulting Reynolds number based on the root chord is $\mathrm{Re}_c = 30.7 \times 10^6$. The transition is fixed at 1% of the chord to reproduce the RANS conditions of a fully turbulent flow. Solutions are obtained on a 573 637 tetrahedral volume element mesh with 82 790 triangular and 85 500 quadrangular surface elements on the inviscid and viscous meshes, respectively. The structural model uses the finest L1 mesh of the wingbox used by Gray and Martins [7] with 71 200 elements. The composite ply properties are consistent with the ones used in the reference. Figure 1 shows the comparison between the wing in baseline configuration and its deformed shape predicted by BLASTER with a Mach number contour plot. The wing is deflected upward and twisted under aerodynamic loads. Table 1 reports the aerodynamic coefficients, the deflection and twist measured at the tip and the maximum material failure criterion of the wing in deformed state. The table also includes a comparison with reference results obtained with the RANS solver ADflow and results obtained without viscous correction using DART with the same setup. The present results indicate that using the VII methodology instead of the classic RANS solver yields similar results for the aerostructural benchmark and provides consistently more accurate results than a purely inviscid computation . The maximum material failure criterion shows the largest discrepancy, whereas aerodynamic coefficients and tip displacements agree well with reference results.

The final article will include the mathematical description of the novel three-dimensional coupled adjoint method implemented in BLASTER used to obtain the partial gradients of the aerodynamic loads with respect to the mesh coordinates and the angle of attack, as well as the complete framework used to perform aerostructural optimization with a VII method. These novelties will be illustrated by considering the optimization cases proposed by Gray and Martins, consisting in structural mass minimization and fuel burn minimization under structural, geometric and performance constraints.

Table 1: Aerodynamic coefficients and structural metrics of the STW in deformed configuration for the aeroelastic analysis benchmark.

Quantity	BLASTER (VII)	ADflow (RANS)	DART (full-potential)
C_L	0.5265	0.5358	0.5646
C_D	0.0190	0.0191	0.0151
Tip deflection (m)	0.6790	0.6860	0.7250
Tip twist (°)	1.5930	1.5500	1.7842
Material failure	0.5050	0.4140	0.5612

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[4] https://github.com/smdogroup/tacs

[5] https://github.com/smdogroup/funtofem

[6] https://github.com/openMDAO/MPHYS

[7] https://github.com/OpenMDAO/OpenMDAO

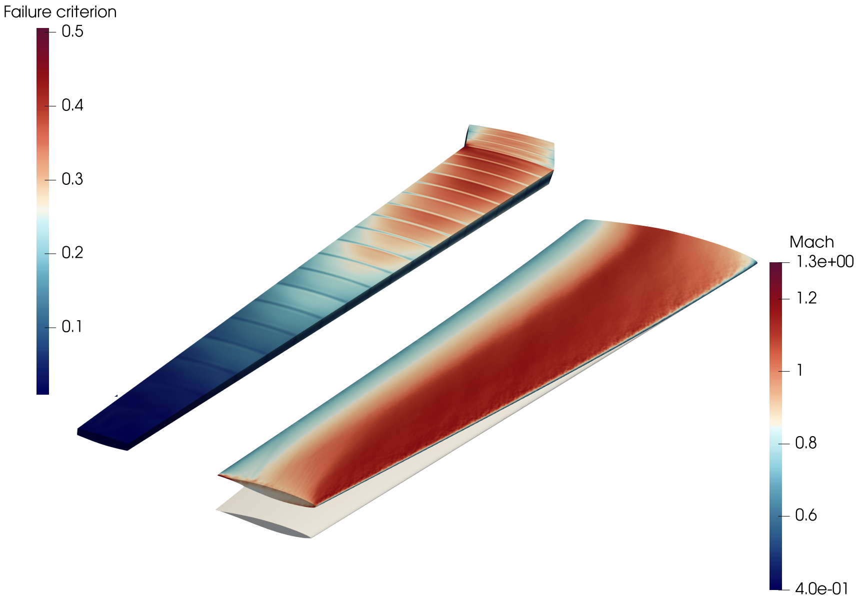

Figure 1: Visualization of the results obtained with the BLASTER-TACS aerostructural model for the STW. In the lower-right corner, the baseline (gray) and the deformed (color) configurations are shown. The Mach number distribution is shown on the deformed state. In the upper-left corner, the failure criterion distribution on the wingbox structure in deformed state is shown.

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