

AEROSTRUCTURAL ANALYSIS AND OPTIMIZATION USING VISCOUS-INVISCID INTERACTION

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Abstract: The use of a Viscous-Inviscid Interaction (VII) method for gradient-based aerostuctural optimization in transonic conditions is investigated. Although high-fidelity RANS-based optimization is increasingly used in aircraft design, the computational cost of these simulations remain rather high for early design stages. Inviscid flow models are on the other hand inexpensive but yield inaccurate predictions of the shock location and aerodynamic coefficients. By including the effect of the boundary layer, VII approaches significantly improve the results of these low-fidelity methods at limited computational cost. VII thus represents an interesting approach to efficiently drive the optimization process towards near-optimal designs that can be subsequently refined using higher-fidelity simulations. In this context, the VII solver BLASTER has been developed and coupled with a full potential solver, supporting optimization with many design variables. To assess the ability of the VII approach to provide meaningful optimized designs, the first two cases of the Simple Transonic Wing (STW) benchmark, proposed by the High-Fidelity Aeroelastic Optimization Benchmark Working Group, are here reproduced. Results show that for the structural sizing in aeroelastic configuration the method reproduces an optimum consistent with the higher-fidelity reference. For the second case, where airfoil shape variables are included, the VII approach leads to a different optimized design than the reference, with stronger rear-loading.

1 INTRODUCTION

Aeroelastic tailoring of composite structures in combination with wing shape optimization is increasingly used during conceptual and preliminary aircraft design stages [1]. These problems involve many geometric and structural design variables and a large number of constraints. In this regard, the High-Fidelity Aeroelastic Optimization Benchmark Working Group introduced the Simple Transonic Wing (STW) benchmark problem [2] in order to standardize the design variables, constraints and objective. This includes several large-scale optimization cases targeting transport aircraft that are suitable for method comparison. The benchmark cases have also been studied by other research groups [3, 4, 5].

Solutions of the Reynolds-Averaged Navier-Stokes (RANS) equations are usually used to model the flow as they provide accurate predictions [2, 3, 6, 7]. However, such simulations are usually expensive. In practice, lower-fidelity models are often used initially, followed by higher-fidelity refinement [3, 8]. For the STW case, it has been shown that a progression of the aerodynamic model fidelity yields a lower wall clock time for the overall optimization [3]. Low-fidelity approaches may introduce inaccuracies, particularly in drag and moment prediction, due to neglected viscous effects and shock misplacement, ultimately resulting in suboptimal designs [7]. Computationally efficient intermediate-fidelity methods that retain the essential physics can help refine the design before starting RANS-based simulations, and thus reduce the computational cost. Viscous-Inviscid Interaction (VII) methods offer such a compromise by including the effect of the boundary layer in the inviscid solution, improving thereby shock prediction and drag estimation at a significantly reduced cost compared to RANS [9, 10].

This work investigates the use of a VII approach to perform efficient and physically consistent aerostructural optimization of flexible wings. A three-dimensional VII scheme, implemented in the solver BLASTER¹, is coupled with a structural solver and leverages efficient gradient computation techniques suitable for large-scale optimizations. The methodology is demonstrated on the STW benchmark [2, 13], highlighting its ability to capture aeroelastic effects at a reduced CPU cost, and thus to drive the design toward a region of the design space where only final refinement and validation with RANS are required.

2 METHODOLOGY

The methodology relies on a coupled aeroelastic framework, in which aerodynamic loads and structural deformations are solved together, with efficient gradient computation techniques to support large-scale optimizations.

2.1 Optimization problem

Gradient-based optimization is used in this work due to its efficiency for problems involving a large number of design variables [14]. The optimization problem consists of minimizing an objective function (e.g. structural mass or fuelburn) with respect to the design variables, subject to equality and inequality constraints enforcing structural, aerodynamic, and geometric requirements. The SQP (Sequential Quadratic Programming) technique is considered to solve the constrained gradient-based optimization problem [15]. In particular, this work uses the SLSQP implementation of the SQP problem [16] that is available in SciPy [17].

¹<https://gitlab.uliege.be/am-dept/blaster> [10, 11, 12]

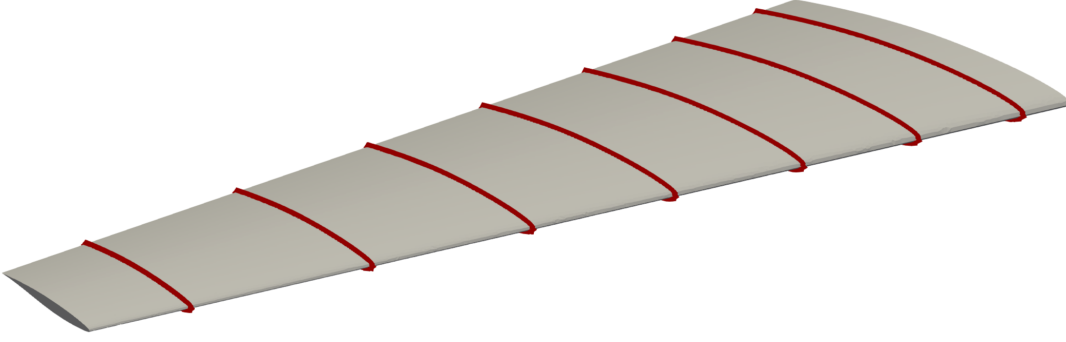


Figure 2: Representation of the boundary-layer sections on a wing. The sections are automatically generated given the number of sections, their spanwise positions and the number of points on each section.

Within this work, the inviscid flow is modeled using the flow solver DART ³ [8, 19, 20]. It solves the full-potential equation using a finite element discretization, which allows to solve transonic flows with embedded weak shock waves.

The flow inside the boundary-layer is computed on each section using a formulation of the integral boundary-layer equations, solved simultaneously with empirical correlations [10, 11, 21, 22]. The boundary layer solution is used to compute the blowing velocity that is subsequently applied as a boundary condition in the inviscid solver. The use of chordwise sections introduces a second structured viscous mesh on the wing, requiring interpolation between the inviscid and viscous meshes. This transfer is performed using Radial Basis Function (RBF) interpolation [23]. To reduce the computational cost, the RBF system is assembled and factorized once on the base meshes, and the resulting operator is reused for all variables throughout the entire optimization, yielding a speed-up of the interpolation step by several orders of magnitude. The resulting approximation has been assessed against an exact interpolation recomputed on the deformed meshes at each step. For the mesh sizes and displacement amplitudes considered in this work, the error introduced by using the base-mesh operator remains below 5%.

2.4 Structural model

The present study employs TACS (The Toolkit for the Analysis of Composite Structures) ⁴ [24, 25] to model the structural response. TACS is an analysis tool for shell structures and has been successfully applied in aerostructural analysis and optimization, including wing-box configurations [2]. TACS is used to compute the structural response under the applied loads, as well as additional response quantities such as the wing-box mass and failure index, used as objective and constraints in the optimization problems. The failure prediction method is described by Gray and Martins [13].

2.5 Multidisciplinary Coupling

The VII-aeroelastic problem is coupled with MPHYS ⁵ [26], a library to solve multiphysics problems based on OPENMDAO ⁶ [27]. MPHYS standardizes the setup of certain kinds of scenarios, in particular the aerostructural scenario considered in this work. All components described above are interfaced with MPHYS and are treated as individual components. OPENMDAO handles the connections between the components and their sequential execution. In

³<https://gitlab.uliege.be/am-dept/dartflo>

⁴<https://github.com/smdogroup/tacs>

⁵<https://github.com/openMDAO/MPHYS>

⁶<https://github.com/OpenMDAO/OpenMDAO>

particular, the VII and aerostructural nonlinear loops are solved iteratively using a Block Gauss-Seidel approach with Aitken relaxation [28].

2.6 Gradients computation

The methodology employed in this work uses a hybrid approach where the total derivatives are computed using the implicit analytic equation, whose partial derivatives are obtained using analytic, Algorithmic Differentiation (AD) or complex step method [14].

The inviscid flow solver DART implements an analytical adjoint method to compute the required gradients. Because of the VII coupling strategy used in this work, the flow is additionally determined based on the blowing velocity on the surface. Furthermore, the outputs of the inviscid component are complemented by the Mach number, the density and the velocity on the surface. As a result, the required additional derivatives have been implemented for the VII coupling.

The gradients of the boundary-layer quantities in BLASTER are obtained using backward AD with the operator overloading strategy with a *taping* technique [29].

The gradients of the RBF operator are obtained using a memory efficient matrix free backward evaluation. Since the RBF operators are assembled once at the calculation startup, only the gradients of the data values are required.

The solver TACS implements an analytical adjoint method to compute the gradients of its outputs, including those of the response quantities described in section 2.4.

The total derivatives are computed by OPENMDAO which solves the global adjoint system. Following Gray and Martins [13], the adjoint system is solved using an iterative flexible GMRES solver [30] from PETSC [31]. At each iteration, the system is preconditioned with one adjoint solve of each discipline.

3 RESULTS

Results are presented for the Simple Transonic Wing (STW) benchmark optimization cases. The benchmark was originally presented in 2024 by Gray and Martins [2], followed by updated solutions in 2025 [13]. The description of all the test cases is available online through the MDO Aeroelastic Benchmark repository ⁷. In the present work, only cases 1 and 2 are considered, which are respectively structural sizing with mass minimization and cruise fuelburn minimization with shape modifications.

The STW is a simple trapezoidal planform with an untwisted RAE2822 cross-section. The wing has a span of 14 m, an aspect ratio of 8.61 and a taper of 0.3. It contains a conformal composite wing-box with skins, spars at the leading and trailing edges and 23 ribs. The available structural model is here fully reproduced in order to stay as close as possible to the reference model [32]. It should be noted that results presented in the reference are also obtained with TACS to model the structure. Three flight conditions are considered, the cruise condition at high Mach number, a pull-up maneuver at 2.5g and a push-down maneuver at -1g. The flight conditions are listed in table 1.

Two meshes are required to perform the VII simulations, the three-dimensional inviscid unstructured mesh and the viscous structured surface mesh. The inviscid mesh is generated using

⁷<https://github.com/MDOBenchmarks/MDOAeroelasticBenchmark>

Table 1: Flight conditions of the STW considered for the benchmark analysis and the two optimization cases.

Conditions	Mach number	Altitude (m)	Load factor
Cruise	0.77	10400	1
Pull-up maneuver	0.458	0	2.5
Push-down maneuver	0.458	0	-1

GMSH [33] and the viscous mesh is generated automatically given the inviscid surface mesh according to two parameters, the number of sections and the number of points on each section. The simulations are run on a 460 000 element inviscid volume mesh with 30 000 nodes on the surface. The viscous solutions are obtained on 100 spanwise sections, equally spaced from 0% to 95% of the span, with 350 chordwise viscous stations each, leading to 35 000 nodes on the surface. The mesh topologies are depicted in figure 3, which shows meshes four times coarser than the meshes used to perform the simulations. The structural mesh is the same as the one used by the reference (finest structural mesh), and an equivalent setup is used in TACS [13].

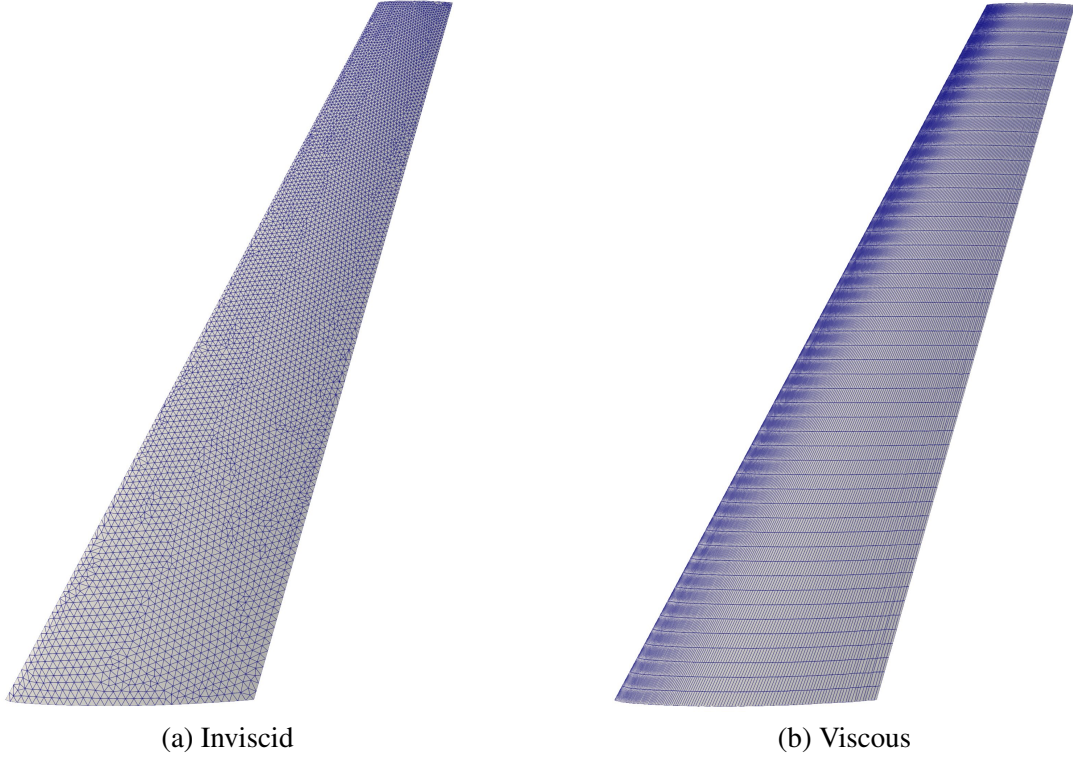


Figure 3: Meshes used for the simulations. The inviscid mesh corresponds to an unstructured volume mesh, of which only the surface mesh is shown in (a), while the viscous mesh shown in (b) is a structured surface mesh used for the boundary-layer computations. The displayed meshes are four times coarser than those used in the simulations.

3.1 Aeroelastic benchmark

Before tackling the optimizations, an aeroelastic benchmark case is considered to quantify the ability of the Viscous-Inviscid Interaction methodology to predict the wing performance in aeroelastic configuration.

The wing is in cruise conditions at an angle of attack $\alpha = 3.25^\circ$ and the inertial loads are set to 1g. The structural variables are the same on all panels. The stiffener pitch is set to 0.15 m, the panel thickness to 0.0065 m, the stiffener height to 0.05 m and the stiffener thickness to 0.006 m. Table 2 presents the key results of the aeroelastic analysis. The lift coefficient, the tip deflection,

the tip twist and the material failure are all within 5% of the reference values obtained with a RANS solver. The drag coefficient is overpredicted by 8.9%, which is substantially better than the inviscid prediction which underestimates this quantity by more than 20%. The same case has been run on a finer 780 000-element inviscid mesh and a finer viscous mesh with 42 000 surface nodes, called "Fine mesh" in table 2, and all the parameters remain within 5% of the presented estimations. For the cruise conditions presented in this benchmark, results obtained with the VII method seems to be suitable for preliminary aircraft design applications.

Table 2: Aerodynamic coefficients and structural metrics of the STW in deformed configuration for the aeroelastic analysis benchmark in cruise conditions at a Mach number of 0.77, angle of attack of 3.25° and where the structure is subject to 1g inertial loads. The base mesh is the mesh of 460 000 volume elements used in the optimization and the fine mesh is composed of 780 000 volume elements.

Quantity	BLASTER (VII)		ADFLOW (RANS)	DART (full-potential)
	Base mesh	Fine mesh		
C_L	0.5355	0.5523	0.5358	0.5646
C_D	0.0208	0.0201	0.0191	0.0151
Tip deflection (m)	0.6520	0.6660	0.6860	0.7250
Tip twist ($^\circ$)	1.5319	1.5660	1.5500	1.7842
Material failure	0.4117	0.4320	0.4140	0.5612

3.2 Optimization results

This section presents the first two optimization cases proposed by Gray and Martins [13]. The first optimization consists in an initial structural sizing through a mass minimization of the wing-box by ensuring no failure for the 2.5g and the -1g maneuvers. The second optimization aims at minimizing the fuelburn in cruise while ensuring no failure in maneuvers.

3.3 Geometry parameterization

The optimization cases considered in this work involve modifications of the wing shape and twist. The geometry of the wing is parametrized using PyGeo⁸ [34], with a free-form deformation (FFD) technique. The FFD uses a control volume defined by control points that map shape modification on a set of embedded points. The FFD volume is defined by 5 spanwise stations with 7 control points on both upper and lower sides, which allows slightly less freedom than the reference but remains consistent with it [13]. The FFD box can be visualized in figure 4.

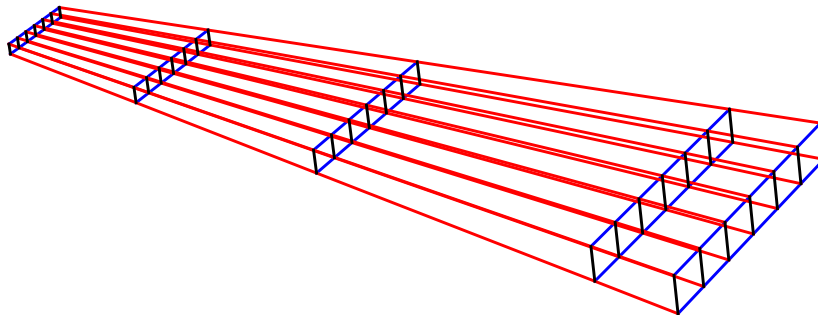


Figure 4: Free-form deformation box used to parametrize the geometry of the wing.

⁸<https://github.com/mdolab/pygeo>

3.4 Objective and constraints computation

After obtaining the aeroelastic solution for the flight conditions listed in table 1, the computation of the objective and different constraints involve multiple stages.

The wing-box mass $M_{\text{wing-box}}$ is to be minimized in case 1, which is an output of the finite-element model. The maneuver should be feasible when the mass of the aircraft is the landing gross mass,

$$M_{\text{LGM}} = M_{\text{payload}} + M_{\text{frame}} + M_{\text{fuel,reserve}} + 2M_{\text{wing}}, \quad (1)$$

where $M_{\text{payload}} = 14.5$ T is the payload mass, $M_{\text{frame}} = 25$ T is the operating empty mass without the wing, $M_{\text{fuel,reserve}} = 2$ T is mass of the fuel reserve. The wing mass is computed using Van Tooren approach [35],

$$M_{\text{wing}} = 10.147(M_{\text{wing-box}})^{0.8162}. \quad (2)$$

Case 2 attempts to minimize the fuelburn. The computation is carried out in two steps. First, the mass at the start of the cruise is computed using the Breguet range equation,

$$M_{\text{cruise,start}} = M_{\text{LGM}} \exp \left(\frac{R_{\text{cruise}} \theta_{\text{TSFC}}}{V_{\text{cruise}}} \left(\frac{D_{\text{cruise}}}{L_{\text{cruise}}} \right) \right), \quad (3)$$

where $R_{\text{cruise}} = 2060$ nm is the nominal cruise range, $\theta_{\text{TSFC}} = 0.64$ 1/h is the specific fuel consumption and V_{cruise} is the true airspeed in cruise (KTAS). The lift and drag are computed using

$$L_{\text{cruise}} = 2L_{\text{wing}} \quad (4)$$

$$D_{\text{cruise}} = 2(D_{\text{wing}} + q_{\text{cruise}} S_{\text{ref}} C_{D,\text{frame}}). \quad (5)$$

where S_{ref} is the half-wing reference surface area, q_{cruise} is the dynamic pressure in cruise and $C_{D,\text{frame}} = 0.01508$ is the drag coefficient of the fuselage, tail and nacelle. The take-off gross mass M_{TOGM} is computed by applying the Breguet equation (3) to the climb segment, using $M_{\text{cruise,start}}$ as final mass, $R_{\text{climb}} = 290$ km and climb speed $V_{\text{climb}} = 320$ mph. The lift and drag in cruise are used for the climb segment. Finally, the fuelburn is computed as

$$M_{\text{fuelburn}} = M_{\text{TOGM}} - M_{\text{LGM}}. \quad (6)$$

The mid-cruise mass is also defined and used to trim the cruise phase,

$$M_{\text{cruise,mid}} = \sqrt{M_{\text{cruise,start}} \times M_{\text{LGM}}}. \quad (7)$$

The second case is subject to the constraint that the volume of the wing is sufficient to contain the fuel. This constraint is expressed as

$$\frac{M_{\text{fuel}}}{\rho_{\text{fuel}}} \leq V_{\text{aux}} + 2k_{\text{tank}} V_{\text{wing-box}} \quad (8)$$

where $M_{\text{fuel}} = M_{\text{fuelburn}} + M_{\text{fuel,reserve}}$ is the fuel mass, $\rho_{\text{fuel}} = 804$ kg/m³ is the fuel density, $V_{\text{aux}} = 2.763$ m³ is the auxiliary fuel tank volume that is not in the wing, $k_{\text{tank}} = 0.85$ is the fraction of the wing-box that can contain fuel and $V_{\text{wing-box}}$ is the wing-box volume, computed from the geometry.

Optimization case 1 - Wing-box mass minimization

The wing-box mass minimization is performed using 446 design variables (listed in table 3), including both structural variables and the angles of attack for the two maneuver conditions. The lift is constrained to $2.5M_{LGM}g$ for 2.5g pull-up maneuver and to $-M_{LGM}g$ for the $-1g$ pull-down maneuver. The failure on both maneuvers is constrained by closely following the reference [13]. The 807 structural constraints are not repeated here for conciseness but closely follow the reference formulation, including adjacency constraints on panel and stiffener thicknesses, stiffener height constraints, stiffener thickness and aspect ratio constraints, and panel length consistency constraints [13]. In total, 814 constraints are enforced in the optimization problem, of which 780 are linear.

Table 3: Objective function and design variables for the optimization case 1.

Category	Quantity	Symbol	Number
Objective	Wing-box mass	$M_{\text{wing-box}}$	1
Design variables	Pull-up maneuver angle of attack	$\alpha_{2.5g}$	1
	Push-down maneuver angle of attack	α_{-1g}	1
	Panel thicknesses	t_{panel}	111
	Stiffener thicknesses	t_{stiff}	111
	Stiffener heights	h_{stiff}	111
	Panel lengths	L_{panel}	111

The optimization ran for 19.7 hours on 3 AMD Ryzen 7 3700X 8-Core (3.6 GHz) processors (59.25 core hours), compared to 31.67 hours on 200 cores (6334 core hours) for the reference using RANS [13]. The evolution of the objective and failure constraints in maneuver are shown in figure 5. At convergence, the wing-box mass is 748.6 kg, 3% heavier than the reference value, also shown in the figure. The failure criterion first increases to twice the allowed value, suggesting that the optimizer initially prioritizes mass reduction. As the optimization progresses, the failure indices decrease and satisfy all constraints. At the end of the optimization, the failure inequality constraints for both maneuvers are active, which is expected. Figure 6 shows the upper and lower skin thickness distributions along the span at the end of the optimization. Overall, the results are in good agreement with the reference solution. The main discrepancy occurs at the kink of the wing-box, where stresses concentrate. At that location, the optimized upper and lower skins are thicker than those of the reference solution, which explains the slightly higher mass obtained in this work. Away from the kink, the thickness distributions decrease and closely match the RANS-based predictions. The twist and normalized lift distributions for both maneuver conditions are shown in figures 7 and 8, respectively, along with the reference optimum for comparison. The baseline configuration at the start of case 1 is also shown in figure 7.

The present method converges to a design close to that obtained with high-fidelity simulations. A final refinement using RANS would likely recover the reference solution more closely.

Optimization case 2 - Fuelburn reduction

For this case, the goal is to minimize the fuelburn in cruise conditions (equation 6) starting from the optimized design obtained in case 1. The structural design variables are the same as for case 1, and the cruise angle of attack, geometrical twist and aerodynamic shape are also considered as design variables. The trim constraints on the maneuver are the same as for case 1, and the cruise

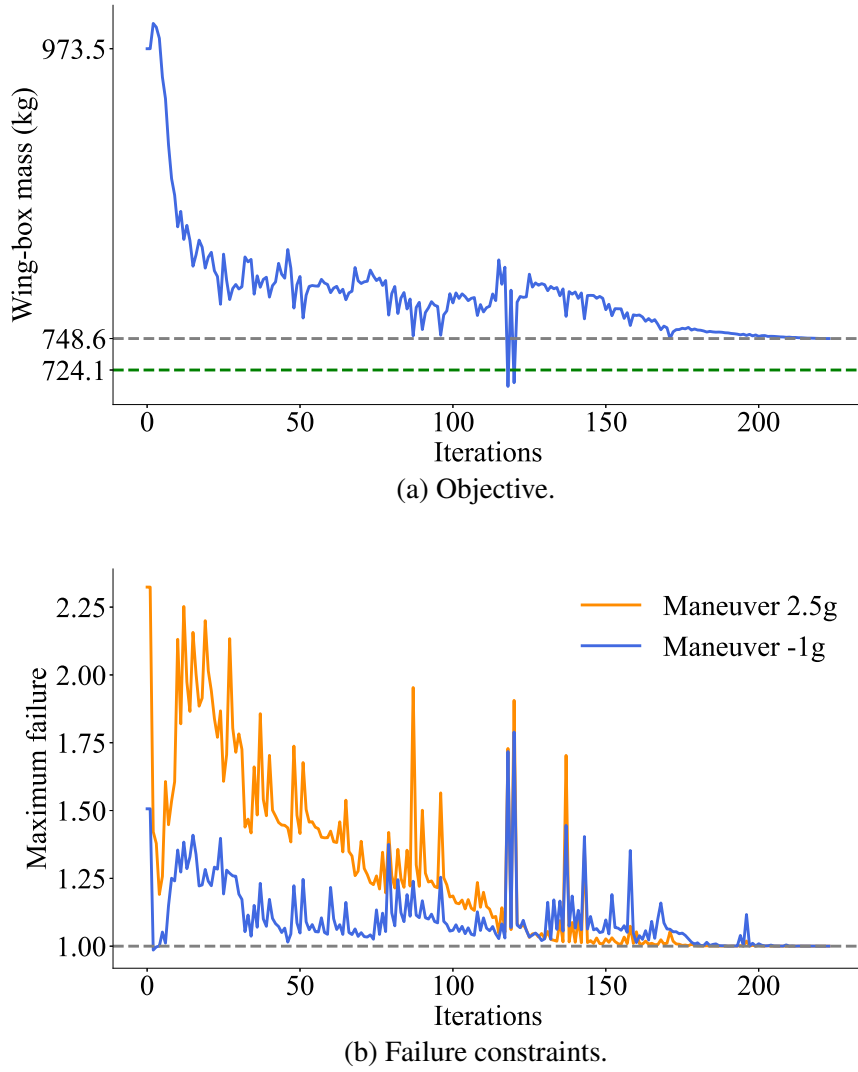
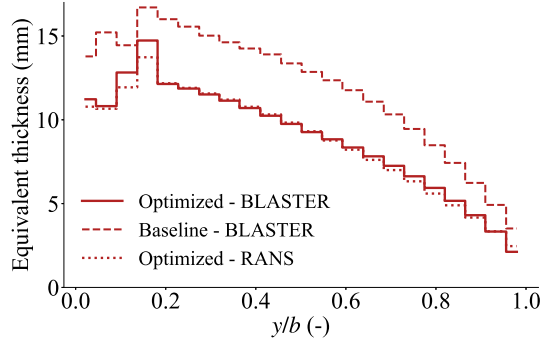


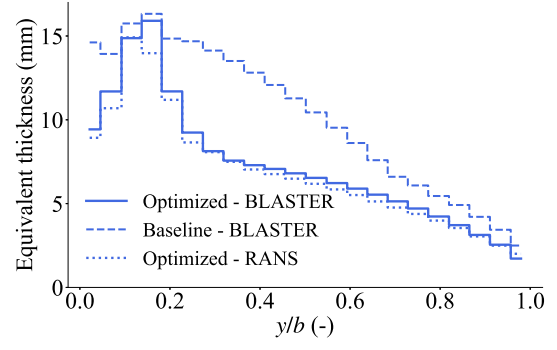
Figure 5: History of the optimization for case 1 where the wing-box mass is minimized under failure constraints in maneuver. The evolution of the objective (a) varies from the initial 973 kg to the optimum predicted at 748 kg. The optimized wing-box mass obtained in the reference [13] is indicated by the dashed green line. The maximum failure constraints for the maneuver cases are shown in (b).

lift is constrained to $1M_{\text{cruise,mid}}$. The geometric constraints follow the reference and include limits on the leading-edge radius, front and rear spar heights, trailing-edge thickness, and fuel volume (equation (8)). The optimization includes 532 design variables and 947 constraints, of which 790 are linear.

The optimization ran for 43.3 hours on 3 AMD Ryzen 7 3700X 8-Core (3.6 GHz) processors (130 core hours), compared to 33.2 hours on 320 cores (10624 core hours) for the reference using RANS [13]. The higher wall clock time is explained by the pull-up maneuver case, which converges in more iterations after shape variations. The history of the optimization is shown in figure 9, where the initial fuelburn of 11.39 t is reduced to obtain the optimum predicted at 10.75 t. The reference RANS-based simulation predicts an initial fuelburn of 11.33 t and a final of 10.98 t. The initial fuelburn predicted in this work is higher than in the reference solution. This can be explained by the fact that the VII formulation tends to slightly overpredict drag compared to the RANS-based approach, as also observed in the aeroelastic benchmark

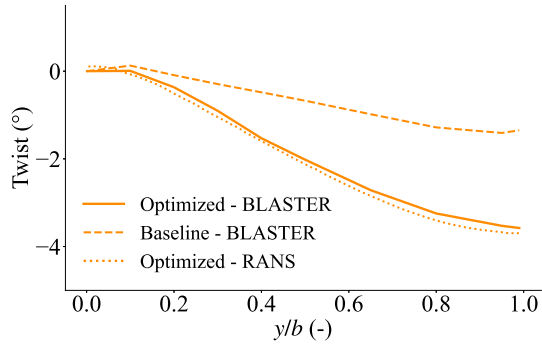


(a) Upper skin.

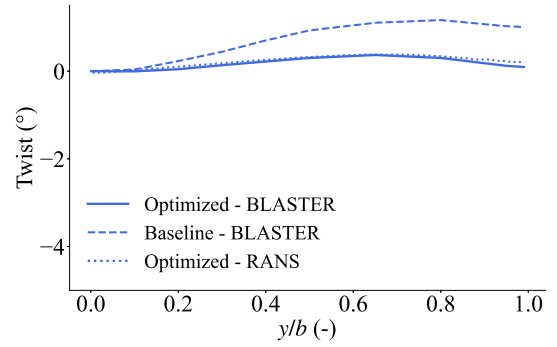


(b) Lower skin.

Figure 6: Equivalent skin thicknesses of the optimized design of case 1 along the wing span. The upper (a) and lower (b) skin thicknesses are shown. Values obtained with the present method are compared to the reference [13] and to the initial values of the parameters.

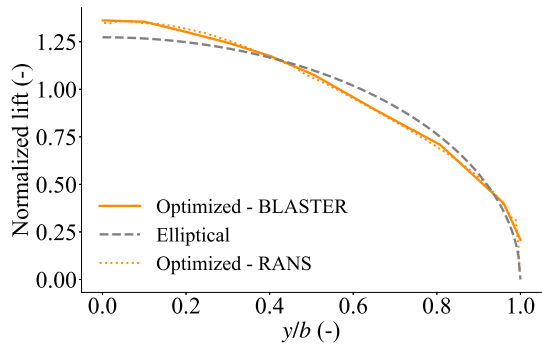


(a) 2.5g pull-up maneuver.

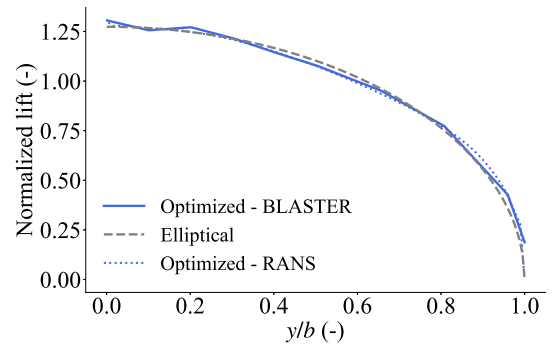


(b) -1g pull-down maneuver.

Figure 7: Twist distributions in the 2.5g (a) and -1g maneuver conditions for case 1. The optimized distributions are compared to the those of the baseline and to the reference obtained using a RANS solver [13].



(a) 2.5g pull-up maneuver.

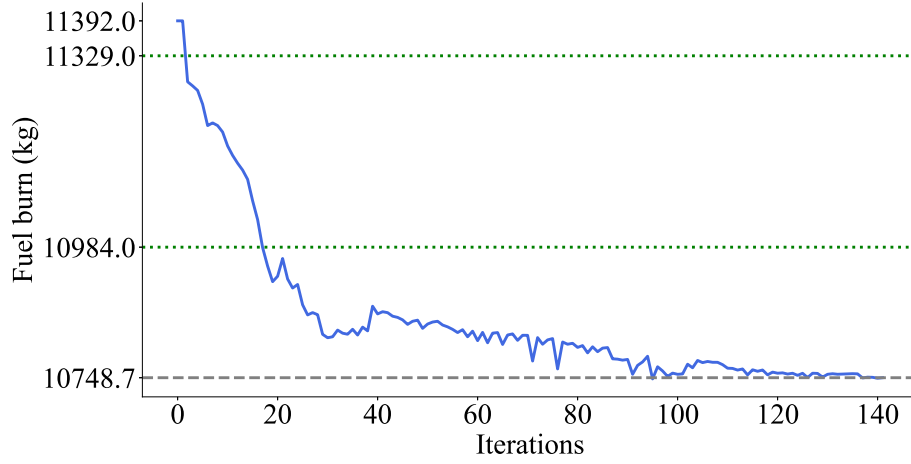


(b) -1g pull-down maneuver.

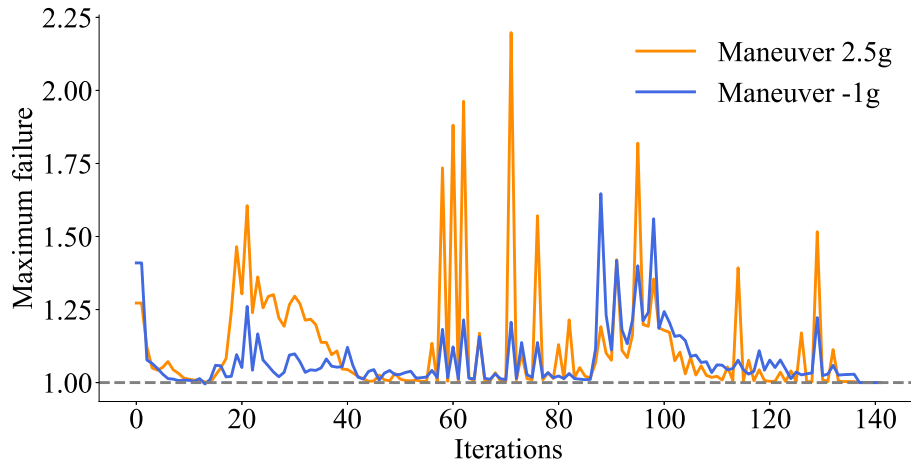
Figure 8: Normalized lift distributions in the 2.5g (a) and -1g maneuver conditions for case 1. The optimized distributions are compared to the those of the baseline and to the reference obtained using a RANS solver [13].

(table 2) and that the initial structural mass obtained in Case 1 is higher than in the reference, which directly increases the fuel urn level in cruise. In the present work, a 5% reduction is observed while the reference study reports a 3% reduction [13]. The final lift-to-drag ratio of the global configuration predicted by the present method is 16.57, while the reference is 16.17

and the final angle of attack in cruise is 2.15 deg, compared to 4.12 deg in the reference. The final optimized designs obtained with the present method and the RANS-based simulations are different, as discussed in the following.



(a) Objective.



(b) Failure constraints.

Figure 9: History of the optimization for case 2 where the cruise fuelburn is minimized by varying the wing geometry. The evolution of the objective (a) varies from the initial 11 392 kg to the optimum predicted at 10827 kg. The reference value at the start (11 329 kg) and the end (10984 kg) of case 2 are also shown [13]. The maximum failure constraints for the maneuver cases are shown in (b).

Figure 10 shows the airfoil profiles at different locations along the span and the corresponding pressure coefficient distributions. The results obtained with BLASTER are compared to the reference solution [13]. The mid-chord shock initially present at inboard stations is removed in the optimized design. This behavior is also observed in the RANS simulation and is directly related to the effect of the local shape design variables. The twist of the optimized design in cruise conditions is decreased, as seen in figure 11. The optimizer decreases the twist to reach a lift distribution closer to the elliptic distribution, shown in figure 12. The main difference with the reference solution is that the wing optimized using BLASTER is strongly rear-loaded. The optimizer reduces drag by flattening the suction-side, which moves the shock wave downstream and weakens its intensity, reducing drag. To maintain the required lift level, negative camber is introduced near the trailing edge on the pressure side. A similar rearward loading of the

optimized design was previously reported with the inviscid solver DART only [8]. From a general point of view, highly-rear loaded configurations are not always desirable, as they lead to a highly negative pitching moment, not taken into account during this optimization.

Given the complexity of the optimization problem, the possibility of a minor difference with the reference, such as a constraint imposed slightly differently, cannot be completely excluded. However, particular attention was paid to reproduce the optimization setup described in the reference study, and all reported constraints were verified to be correctly implemented in the present framework. The minor differences that exist between the present work and the reference study include the optimizer and the number of degrees of freedom in the FFD parameterization, which are not expected to fully explain the discrepancies between the optimized designs. Several tests were conducted to identify the possible origin of the observed differences. These include modifying the scaling of the objective and constraint functions in the optimizer, increasing the number of degree of freedom of the FFD box and modifying the shape constraints to favor front-loaded designs. All these investigations led to similar rear-loaded wing designs. The next step would be to constrain the pitching-moment coefficient of the wing to prevent the rear-loading, but this would change the scope of the proposed optimization.

To investigate the relevance of the optimum obtained in the present work, the optimized design reported in the reference [13] is simulated in cruise conditions using BLASTER. The analysis is performed by prescribing the reference design-variable values and carrying out an aeroelastic simulation. Figure 13 presents the pressure coefficient at two spanwise stations for this configuration. Despite small oscillations in the leading edge region, results show good agreement with the reference solution. In particular, the lift-to-drag ratio is predicted to be 16.05, compared to 16.17 obtained from the RANS-based simulation [13]. Consequently, the observed discrepancies between the optimized designs can be interpreted in two ways. The first is that the present method identifies a genuinely improved design compared to the reference solution. In this case, the higher predicted lift-to-drag ratio and lower cruise angle of attack would correspond to a physically relevant improvement of the optimized configuration. Confirmation of this hypothesis would require a higher-fidelity RANS aerodynamic analysis on the final optimized geometry obtained in the present work. The second possibility is that the differences arise from limitations in the aerodynamic fidelity of the present approach. In particular, the method may favor more rear-loaded wing designs and predict optimistic aerodynamic performance for such configurations, compared to RANS-based simulations. In this case, the improved lift-to-drag ratio predicted by the present method would not correspond to a true performance gain. This can be investigated further by considering a higher-fidelity Euler, rather than a full potential inviscid flow solver to model the inviscid flow, which may provide predictions more consistent with the RANS-based results.

4 CONCLUSION

This work aims at showing the use of a Viscous-Inviscid Interaction (VII) framework for large-scale aeroelastic analysis and optimization to quickly assess the performance of a configuration and provide improved starting points for high-fidelity RANS-based optimizations. The objective is not to replace RANS solvers, but to reduce the computational cost of early-stage design by driving configurations close the optima of interest before engaging expensive high-fidelity aerodynamic solvers, as proposed by Jacobson *et. al.* [3].

To achieve this, the VII methodology implemented in BLASTER was integrated within a coupled aeroelastic optimization framework. The approach combines an inviscid full-potential

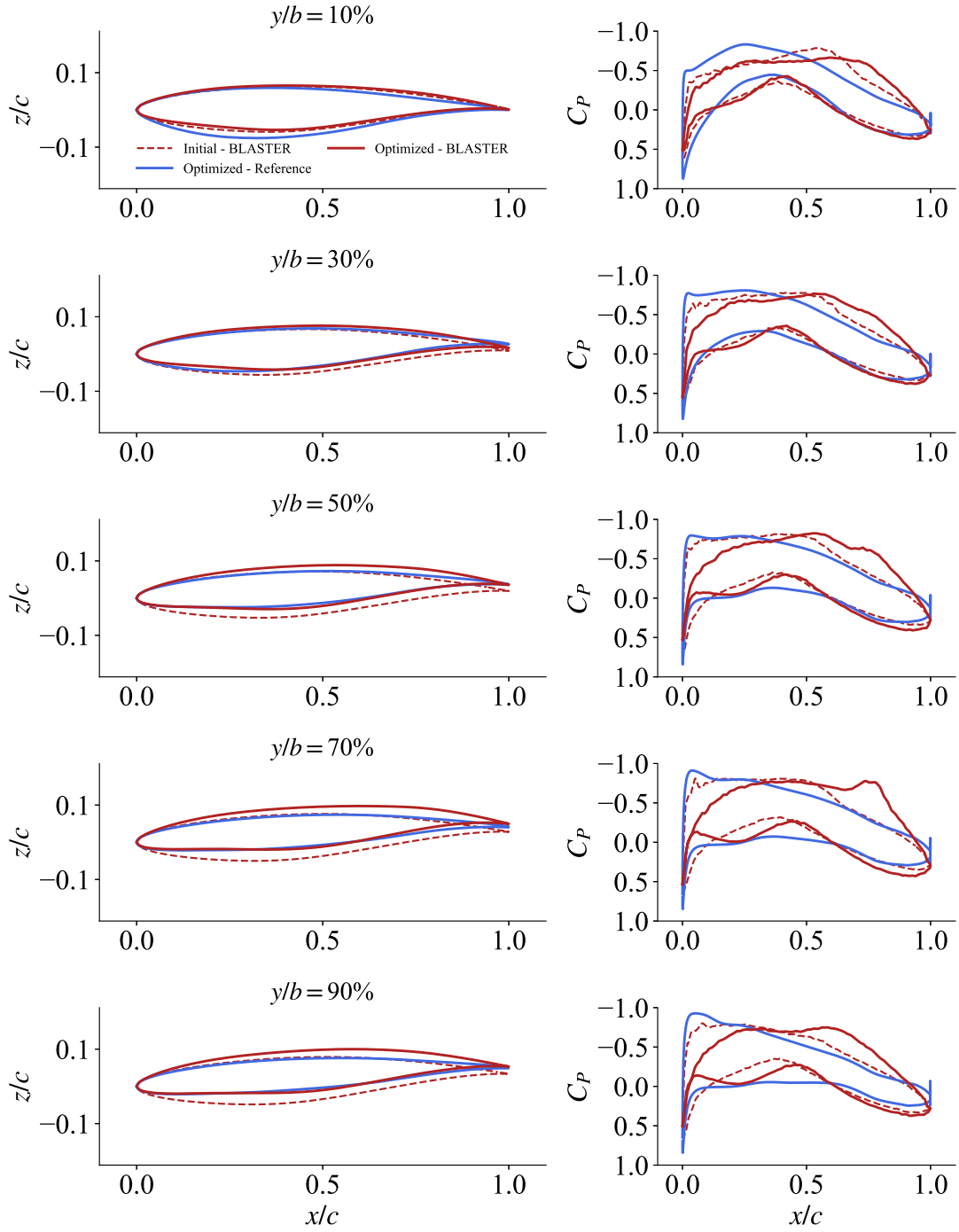
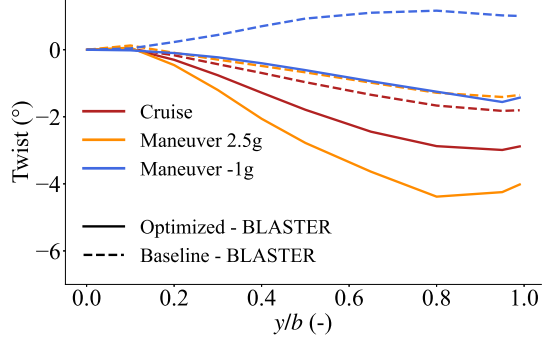


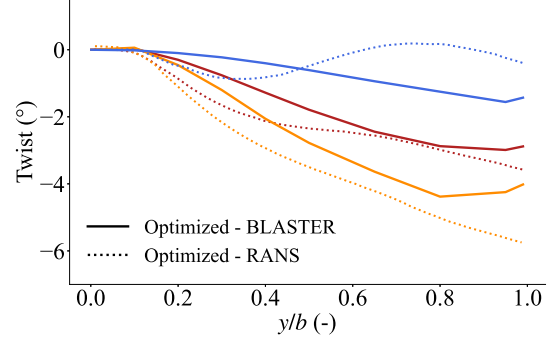
Figure 10: Profiles and pressure distributions at different spanwise positions for case 2.

solver with a boundary-layer model, allowing for improved prediction of drag and shock location compared to purely inviscid methods, while requiring a lower CPU computational cost than RANS. The use of adjoint-based gradient computation enables the efficient treatment of large-scale optimization problems.

The results obtained on the Simple Transonic Wing benchmark demonstrate that the proposed methodology provides accurate aeroelastic predictions, with good agreement with RANS results for key quantities such as loads, structural response, and drag. In the first optimization, a structural sizing by minimizing the mass was considered. The proposed approach converges to a design close to the RANS-based optimum at a fraction of the computational cost, confirming

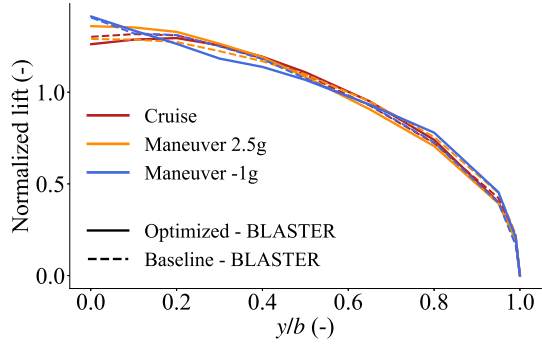


(a) Comparison with the case 2 baseline design.

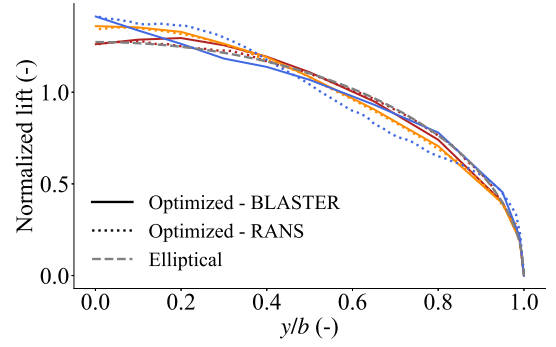


(b) Comparison with the RANS-based case 2 optimized design.

Figure 11: Twist distributions for case 2. The optimized distributions of case 2 are compared to the baseline of case 2 (optimized design of case 1) (a) and to the reference optimized design obtained using a RANS solver (b) [13].



(a) Comparison with the case 1 optimized design.



(b) Comparison with the RANS-based case 2 optimized design.

Figure 12: Normalized lift distributions for case 2. The optimized distributions of case 2 are compared to those of the optimized design of case 1, used to start case 2 (a) and to the reference optimized design obtained using a RANS solver (b) [13].

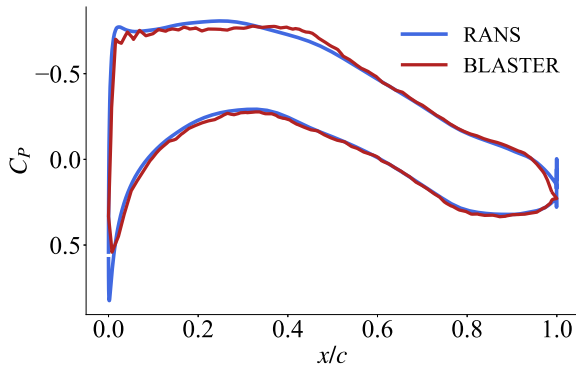
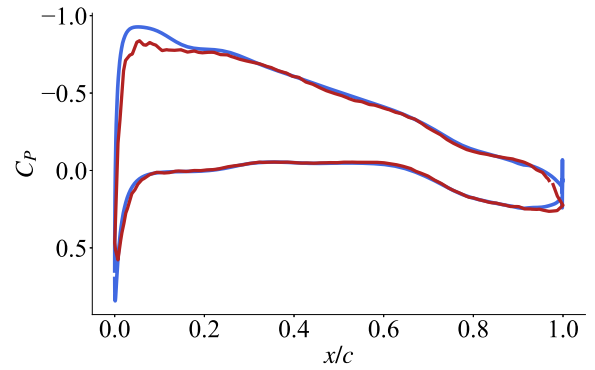
(a) $y/b=30\%$ (b) $y/b=90\%$

Figure 13: Comparison of the pressure distribution on the RANS-based optimized geometry [13]. The figure presents the pressure coefficient distributions at an inboard section ($y/b = 30\%$) and outboard section ($y/b = 90\%$), comparing the values obtained with BLASTER on the RANS-based optimized design against the reference solution itself.

that these models can be used at the start of the optimizations. This makes the method useful at the onset of large-scale optimizations, where rapid exploration of the design space is required.

The second optimization case, involving shape modifications, highlights some discrepancies between the present approach and the reference solution. The optimization led to an unexpected rear-loaded wing. While these designs are optimal for the VII model, they may not remain optimal or feasible when evaluated with higher-fidelity methods. This aspect needs to be investigated further.

Future work will address these limitations. First, the optimized geometries obtained with BLASTER will be evaluated using RANS simulations to determine whether the rear-loaded wing leads to higher drag. Second, the use of an alternative inviscid solver based on the Euler equations, with an adjoint method, will be investigated. This could improve the robustness of the optimization process and lead to a better understanding of the results.

Overall, the proposed VII-based framework represents a promising compromise between accuracy and computational efficiency, enabling more effective use of high-fidelity tools by providing better initial designs for subsequent refinement.

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