ACCELERATED CONVERGENCE OF HIGH-FIDELITY AEROELASTICITY USING LOW-FIDELITY AERODYNAMICS

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Roeland De Breuker
Delft University of Technology

ACCELERATED CONVERGENCE OF HIGH-FIDELITY AEROELASTICITY USING LOW-FIDELITY AERODYNAMICS

K. Jovanov[1] and R. De Breuker[1]

[1] Delft University of Technology
Kluyverweg 1, 2629 HS Delft, The Netherlands
k.jovanov@tudelft.nl

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Abstract: This paper presents a methodology on how to effectively solve static high-fidelity aeroelastic problems for high-subsonic and transonic flow regimes. The idea is to employ a low-fidelity aerodynamic model to reduce the computational cost of the high-fidelity aeroelastic problem. The low-fidelity model, in this work a linear aerodynamics model, is used systematically through a model management strategy to accelerate the convergence of the high-fidelity aeroelastic equilibrium. The high-fidelity aerodynamic model is discretized by the finite volume method and the Euler equations are solved in SU^2. The structural model is a geometrically non-linear beam element model.

1 INTRODUCTION

With most commercial airliners operating in transonic flight conditions, it would only seem beneficial to employ Computational Fluid Dynamics (CFD) tools when performing Multidisciplinary Design Optimization (MDO). Nonlinear flow phenomena, e.g. shocks and flow separation, arise in transonic flight and can only be accurately predicted by CFD models. The possibility of adopting these models in MDO frameworks has been encouraged by recent advancements in parallel computing and ever-growing computational resources. Despite this, CFD tools are still considered impractical in preliminary design stages mainly due to the high computational cost. Consequently, it is not computationally viable to perform aeroelastic optimization using high-fidelity (HiFi) aerodynamics such as CFD in preliminary design stages.

Much work has been dedicated to improve the computational efficiency and robustness of HiFi aeroelastic analysis and sensitivity analysis in gradient-based optimization. Barcelos et al. [1] implement a Schur complement reduction on the steady-state aeroelastic system to formulate a system comprising of the fluid mesh points on the fluid-structure interface. The aeroelastic analyses and the sensitivity analyses are solved using Newton's method and the linear system for each Newton iteration is solved with a Krylov subspace method. The authors found that the resulting "Schur-Newton-Krylov" solver is more efficient and robust compared to conventional staggered schemes augmented by various relaxation schemes.

Kennedy et al. [2] compare four different solution methods for aerostructural analysis and optimization. Moreover, the aerostructural system, composed of a finite element solver coupled to an in-house panel code, is solved in parallel to speed up convergence. Parallelism is applied on three levels: optimization level, system-level and discipline-level. The computation time of the aeroelastic problems have shown to scale well with the number of cores and increased efficiency is achieved through parallel computation.

Modern-day industrial analysis and optimization tools often rely on panel methods for load prediction. The main advantage is that they provide good results of aerodynamic properties at a low computational cost. However, the validity of their results are becoming increasingly questioned, in particular for transonic regimes, and pressure exists to perform MDO with more complex models [3]. The idea of using low-fidelity (LoFi) models to alleviate the computational burden of HiFi analysis and optimization problems is an attractive prospect that has caught the attention of several authors.

Choi et al. [4] present a hierarchical multi-fidelity design approach for the optimization of a low-boom supersonic business jet. Response surfaces are generated for both levels of fidelity and only the aerodynamic optimization problem is solved. No aeroelasticity is considered in this work. The optimization problem is solved in a surrogate-based approach using the Nelder-Mead simplex method.

Balabanov and Venter [5] use HiFi analysis to obtain responses and LoFi analysis to generate gradients for a gradient-based optimizer in structural optimization. They are of the opinion that the gradients used in the optimizer may be of relatively low quality, as long as the general trend of the gradient vector is captured correctly. The main advantage is that the LoFi gradients are cheap to obtain. The optimizer will however most likely converge in the vicinity of the HiFi optimum, rather than pinpointing the exact location.

The objective of this work is to reduce the computational cost of static HiFi aeroelasticity by systematic use of an auxiliary LoFi aerodynamic model. A defect-correction methodology is implemented as described in Jovanov et al. [6] and additional improvements are made to converge the nonlinear aeroelastic model to a state of equilibrium. The overall goal is to reduce the number of function calls of the HiFi aerodynamic solver, as this is usually the computationally costliest part of the aeroelastic analysis.

The remainder of this paper is organized as follows: the flow and structural solvers together with the fluid-structure coupling scheme are discussed in Section 2. The proposed method is then explained in detail in Section 3. A case study is performed to demonstrate the potential benefits of the proposed method in Section 4, followed by conclusions and recommendations for future work in Section 5.

2 COMPUTATIONAL MODULES AND COUPLING SCHEME

2.1 Aerodynamic analysis

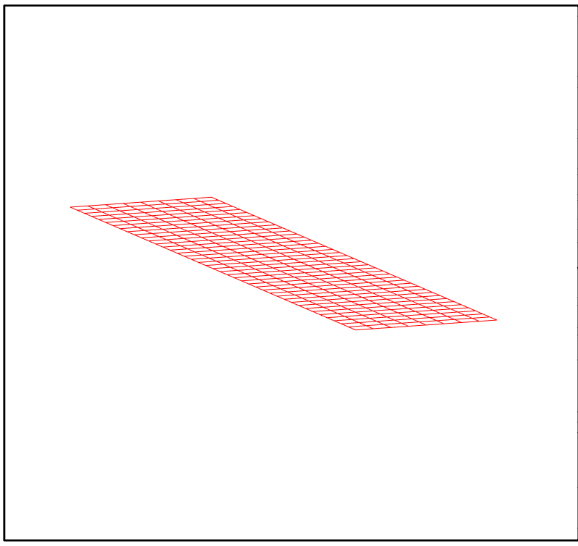
Two aerodynamic modules are required in this work: one solving a set of LoFi equations and another solving a set of HiFi equations. The former falls under the category of panel methods where vortex ring elements are used to approximate the aerodynamic solution. The panels are distributed on the camber surface on the wing (see Figure (1)) and not on the aerodynamic surface. This typically generates small discrepancies in the results, which is known as the "thickness effect". The discrete form of the linearized potential flow equations can be expressed as:

$$\tilde{\mathcal{R}}_{\mathrm{a}}(\boldsymbol{\gamma},\mathbf{x}_{\mathrm{p}}) = \mathbf{A}\boldsymbol{\gamma} - \mathbf{b} \tag{1}$$

where $\boldsymbol{\gamma}$ is the unknown vector of vortex strengths, $\mathbf{x}_{\mathrm{p}}$ are the panel coordinates, $\mathbf{A}$ is the matrix of influence coefficients and $\mathbf{b}$ is the Neumann boundary condition vector. The influence coefficient matrix is purely a function of geometry and can be assembled through repeated application of the Biot-Savart law. Once the linear system (1) is solved, the aerodynamic loads can be obtained in a post-treatment step with the Kutta-Joukowski theorem:

$$\tilde{\mathbf{f}}_{\mathrm{a}} = \rho_\infty \mathbf{V}_\infty \times \boldsymbol{\gamma} \tag{2}$$

where ρ_∞ and $\mathbf{V}_\infty$ are the free-stream density and free-stream velocity vector, respectively. To account for compressibility effects in high-subsonic flows a Prandtl-Glauert correction rule is applied to the aerodynamic loads. The methods for obtaining the LoFi aerodynamic loads are in accordance with, and can be further studied in Katz and Plotkin [7].



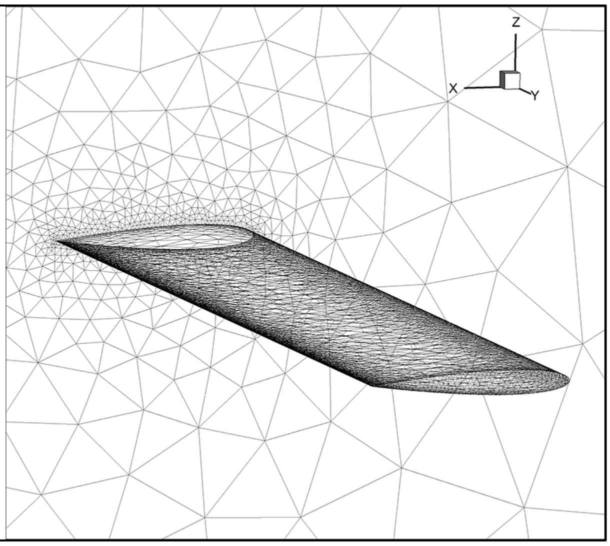


Figure 1: Panel discretization

Figure 2: Finite volume discretization

In addition to aerodynamic loads, the LoFi aerodynamic module needs to generate the aerodynamic stiffness matrix $\mathbf{K}_{\mathrm{a}}$. This matrix describes how aerodynamic loads change with respect to perturbations on the structural degrees of freedom and will be described in more detail in Section 3.

The main shortcoming of the panel method described above is that its application is limited to attached flow conditions in the high-subsonic regime. Panel methods in general lack the predictive capability of modeling nonlinearities in transonic flow. To address this shortcoming, a more advanced aerodynamic solver is required. The HiFi aerodynamic module in this paper is the open-source CFD and optimization tool, SU^2 [8]. The compressible Euler equations are solved to account for recompression shocks. The discrete equations can be expressed in residual form as:

$$\mathcal{R}_{\mathrm{a}}(\mathbf{w},\mathbf{x}_{\mathrm{v}}) = 0 \tag{1}$$

where $\mathbf{w}$ is the vector of fluid state variables and $\mathbf{x}_{\mathrm{v}}$ are the volume grid coordinates. The output of any CFD solver for steady-state analysis is typically available as converged surface pressure distribution. It is therefore necessary to integrate the pressure to obtain the aerodynamic loads on the surface.

2.2 Structural analysis

The structural solver should prove capable of estimating internal forces or stress resultants $\mathbf{f}_\mathrm{i}$ as a function of structural deformation $\mathbf{u}$. In addition, the tangent stiffness matrix $\mathbf{K}_\mathrm{s}$ need to be accessible. In the case of a linear-elastic structure the stiffness matrix need only be evaluated once and then stored in memory for subsequent analyses. The internal forces can be evaluated in a straightforward manner by multiplying the stiffness matrix with the structural deformations. In nonlinear structural analysis this is no longer the case. The stiffness matrix will not remain constant throughout the analysis and needs therefore be updated. The generic solution for the structural equations in residual form can be expressed as:

$$\mathcal{R}_\mathrm{s}(\mathbf{u}) = \mathbf{f}_\mathrm{i}(\mathbf{u}) - \mathbf{f}_\mathrm{a}(\mathbf{u}) \tag{2}$$

where $\mathbf{f}_\mathrm{a}$ is the vector of external aerodynamic loads. It should be emphasized that the aerodynamic loads are only implicitly dependent by structural deformations. In this paper the structural model is a finite element beam model using linear Timoshenko beam elements. The elements are coupled in a co-rotational framework to obtain a geometrically non-linear structural solution.

2.3 Fluid-structure coupling scheme

Configurations of non-conforming fluid and structural grids are frequent in computational aeroelasticity. Whereas the structural model adopts a Lagrangian framework, the flow dynamics is described by an Eularian framework. The discretized structural mesh will therefore translate and rotate with the deformations while the fluid mesh remains fixed. Consequently, a mechanism is needed to; 1) transfer the aerodynamic loads from the aerodynamic grid to the structural nodes and 2) deform the aerodynamic grid with respect to the structural deformations (see Figure (3)).

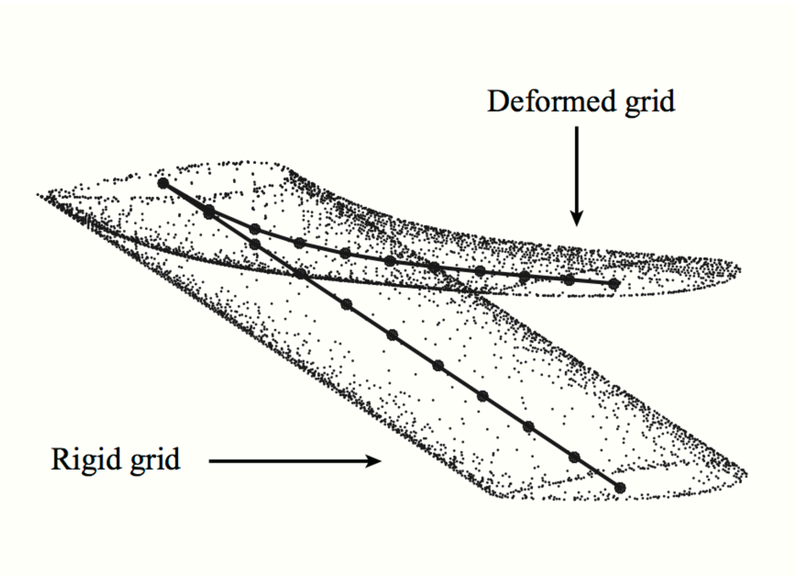


Figure 3: Scatter plot of rigid and deformed surface grid

To this end, we apply a coupling method based on the principle of equivalence of work [9, 10]. The virtual work done by the aerodynamic loads on the aerodynamic model should be equal to the virtual work done by the equivalent aerodynamic loads on the structural model:

$$\delta W = \delta \mathbf{u}_a^T \cdot \mathbf{f}_a = \delta \mathbf{u}_s^T \cdot \mathbf{f}_s \tag{3}$$

Using this expression a coupling matrix $\mathbf{H}$ can be formulated such that:

$$\mathbf{u}_a = \mathbf{H} \cdot \mathbf{u}_s \tag{4}$$

$$\mathbf{f}_s = \mathbf{H}^T \cdot \mathbf{f}_a \tag{5}$$

Two coupling matrices are constructed in a pre-processing step using radial basis functions: one coupling matrix for the LoFi aerodynamic model and another for the surface grid of the CFD model. An additional matrix is constructed for the CFD model to deform the volume grid based on the already updated surface grid.

3 AEROELASTIC ANALYSIS

3.1 Newton's method

Newton's method is an effective solution strategy known to exhibit quadratic rates of convergence in the proximity of the solution. The method can be derived from a first-order Taylor series expansion of the structural residual (4):

$$\left(\frac{\partial \mathbf{f}_i}{\partial \mathbf{u}}\right)^{(n)} \Delta\mathbf{u} + \mathbf{f}_i^{(n)} = \left(\frac{\partial \mathbf{f}_a}{\partial \mathbf{u}}\right)^{(n)} \Delta\mathbf{u} + \mathbf{f}_a^{(n)} \tag{8}$$

The first gradient term describe how internal forces change due to structural deformations. This is the structural tangent stiffness matrix, which can be obtained by the structural solver. The second gradient term is often denoted the aerodynamic stiffness matrix, $\mathbf{K}_a$, since it describes how aerodynamic loads change with structural perturbations. Rearranging the above equation results in Newton's method:

$$\left(\mathbf{K}_s^{(n)} - \mathbf{K}_a^{(n)}\right)\Delta\mathbf{u} = -\mathcal{R}_s^{(n)}, \quad \mathbf{u}^{(n+1)} = \Delta\mathbf{u} + \mathbf{u}^{(n)} \tag{9}$$

The aerodynamic stiffness matrix can be difficult to obtain for HiFi systems, as it entails information from both the aerodynamic as well as the structural system. Furthermore, the additional computational cost of evaluating this matrix significantly degrades the efficiency of Newton's method. To reduce the computational cost Gerbeau and Vidrascu [11] propose to substitute this matrix with an approximated matrix constructed by an inexpensive linear aerodynamics model. In this paper the panel method described in Section 2.1 is utilized to construct the approximated aerodynamic stiffness matrix:

$$\widetilde{\mathbf{K}}_a = \mathbf{H}^f \rho_\infty \mathbf{V}_\infty \mathbf{A}^{-1} \frac{\partial \widetilde{\mathcal{R}}_a}{\partial \mathbf{x}_p} \mathbf{H}^d \tag{10}$$

where $\mathbf{H}^f$ is the splining matrix that interpolates the loads from the panels to the structural nodes and $\mathbf{H}^d$ is the splining matrix that interpolates displacements from the structural nodes to the panels. The sensitivity of the aerodynamic residual (1) with respect to the panel coordinates requires additional explanation. This term can be defined as:

$$\frac{\partial \tilde{\mathcal{R}}_{\mathrm{a}}}{\partial \mathbf{x}_{\mathrm{p}}} = \frac{\partial \mathbf{A}}{\partial \mathbf{x}_{\mathrm{p}}}\boldsymbol{\gamma} - \frac{\partial \mathbf{b}}{\partial \mathbf{x}_{\mathrm{p}}} \tag{11}$$

To analytically obtain the sensitivities of the influence coefficient matrix with respect to the panel coordinates the derivate of the Biot-Savart law is applied. The resulting third-order tensor requires vast amount of storage space, hence it is advised to keep the number of panels as low as possible.

3.2 Proposed method: Defect-correction approach

The proposal of this work is to circumvent Newton's method for a HiFi problem by solving a LoFi aeroelastic equation while adding an aerodynamic correction load. The rationale of using a correction load is to rectify the convergence from the LoFi equilibrium to the HiFi equilibrium and concurrently reduce the computational cost. The method can be derived by subtracting LoFi loads in the structural residual (4):

$$\mathbf{f}_{\mathrm{i}}(\mathbf{u}) - \tilde{\mathbf{f}}_{\mathrm{a}}(\mathbf{u}) = \mathbf{f}_{\mathrm{a}}(\mathbf{u}) - \tilde{\mathbf{f}}_{\mathrm{a}}(\mathbf{u}) \tag{12}$$

The right-hand side of Equation (11) is mostly considered to be a frozen load and is only updated every k^{th} iteration. This difference in aerodynamic load is denoted the correction load $\Delta\mathbf{f}_{\mathrm{a}}$. The left-hand side is expanded to form a first-order Taylor series:

$$\left(\frac{\partial \mathbf{f}_{\mathrm{i}}}{\partial \mathbf{u}}\right)^{(\mathrm{n})} \Delta\mathbf{u} + \mathbf{f}_{\mathrm{i}}^{(\mathrm{n})} - \left(\frac{\partial \tilde{\mathbf{f}}_{\mathrm{a}}}{\partial \mathbf{u}}\right)^{(\mathrm{n})} \Delta\mathbf{u} - \tilde{\mathbf{f}}_{\mathrm{a}}^{(\mathrm{n})} = \Delta\mathbf{f}_{\mathrm{a}}^{(\mathrm{k})} \tag{6}$$

The terms can be reordered to formulate the Defect-correction equation:

$$\left(\mathbf{K}_{\mathrm{s}}^{(\mathrm{n})} - \tilde{\mathbf{K}}_{\mathrm{a}}^{(\mathrm{n})}\right)\Delta\mathbf{u} = -\tilde{\mathcal{R}}_{\mathrm{s}}^{(\mathrm{n})} + \Delta\mathbf{f}_{\mathrm{a}}^{(\mathrm{k})}, \quad \mathbf{u}^{(\mathrm{n}+1)} = \Delta\mathbf{u} + \mathbf{u}^{(\mathrm{n})} \tag{14}$$

where $\tilde{\mathcal{R}}_{\mathrm{s}}^{(\mathrm{n})}$ is the LoFi load residual. Noticeable is that Equation (14) resembles Newton's method (9). The major difference is that the Defect-correction equation is a solution to the LoFi aeroelastic problem. However, at convergence the LoFi load in the correction term will cancel the LoFi load in the residual term. The outcome is a state of equilibrium where the internal structural forces equal the HiFi aerodynamic loads in the correction term.

3.3 Load increments for nonlinear structural analysis

An important topic must be addressed when structural models exhibit highly nonlinear behaviour. Flexible structures subject to high aerodynamic loads will result in large displacements and any effort to solve the static aeroelastic problem without using load increments is likely to fail. It is therefore imperative to combine Newton's method or the Defect-correction method with an incremental approach to maintain robustness in the solution procedure. The number of load increments can be adapted during the analysis. For instance, if a load increment is solved in less than 3 iterations the subsequent load increment can be doubled to reduce the computation time. Conversely, if the number of iterations exceeds 8, the subsequent load increment is halved to increase the robustness.

Additionally, it should be emphasized that force equilibrium is not a requirement for each load increment. It should merely result in a sufficient approximation such that subsequent increments can proceed without diverging. It is however of great importance that the final increment is converged properly, as this is the static aeroelastic deflection that is sought for.

3.4 Aerodynamic model management

To accelerate the convergence of the static HiFi aeroelastic problem, which is the objective of this paper, a study is needed to determine the proper use of the two aerodynamic models at our disposal. A model management strategy needs to be formulated. To this end, a wing configuration with a 5m semispan and a constant chord of 1m is studied. The wing features no sweep and has a symmetric airfoil profile of NACA0012. It is subject to a symmetry condition on the y-axis and has a free-stream pressure, density and angle-of-attack of 26437 N/m^2, 0.4127 kg/m^3 and 2.5 degrees, respectively. The lift coefficient and the moment coefficient about the mid-chord on the rigid wing are depicted for varying free-stream Mach numbers in Figures (4) and (5), respectively.

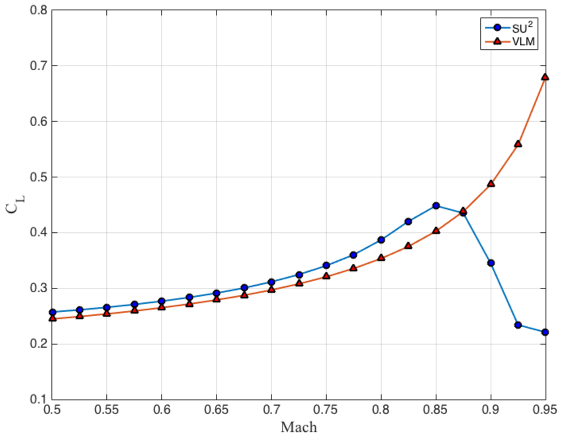


Figure 4: Lift coefficient vs Mach number

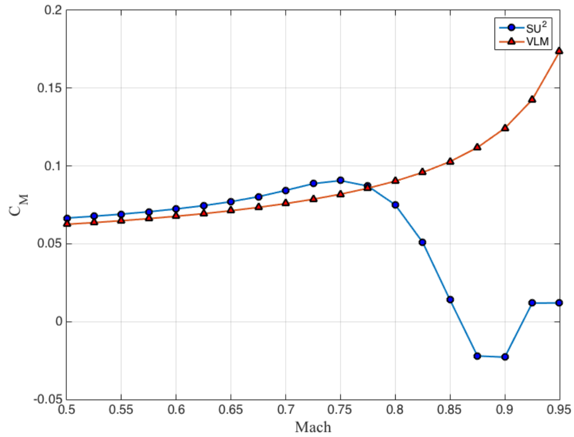
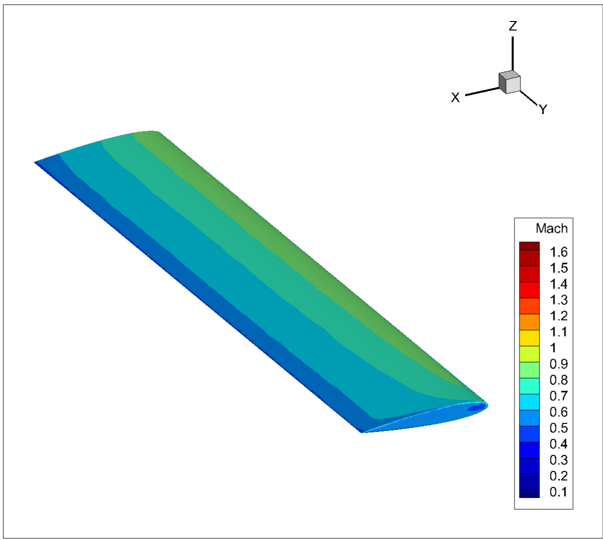


Figure 5: Moment coefficient vs Mach number

It can be observed that the results of the two models match well for free-stream Mach numbers up to 0.70. The small discrepancies for low Mach numbers are mainly due to the thickness effect as explained in Section 2.1. The wing enters transonic flight for Mach numbers exceeding 0.70. At these Mach numbers the results from the LoFi become unreliable. The lift coefficient goes to infinity when the Mach number reaches unity due to the Prandtl-Glauert correction rule. Strong recompression shocks evolve in the proximity of the trailing edge as depicted in Figure (7).



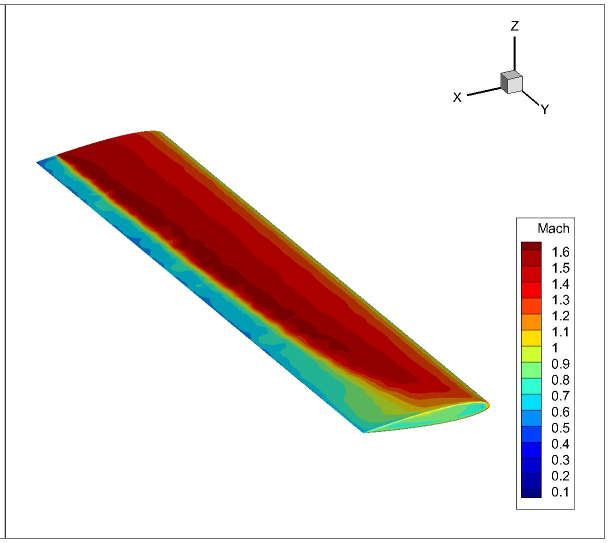
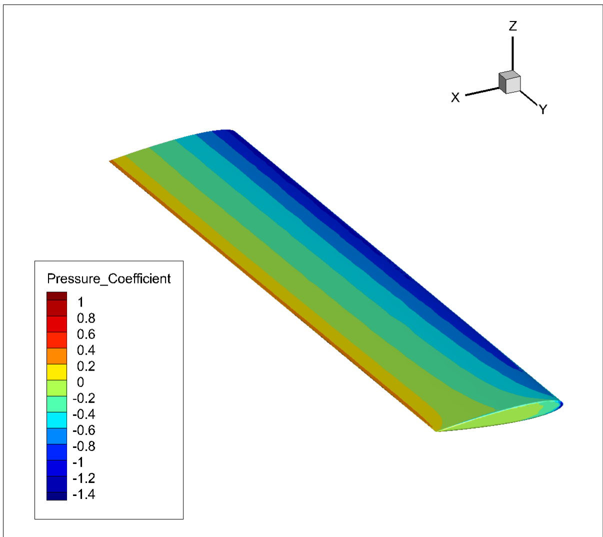


Figure 6: Local Mach for rigid wing $M_\infty = 0.60$

Figure 7: Local Mach for rigid wing $M_\infty = 0.85$

The progressive displacement of the pressure from the leading edge to the trailing edge is reflected in Figure (9). The pressure is clearly dominant at the trailing edge for Mach 0.85. That also explains the sudden drop of the moment coefficient in Figure (5).



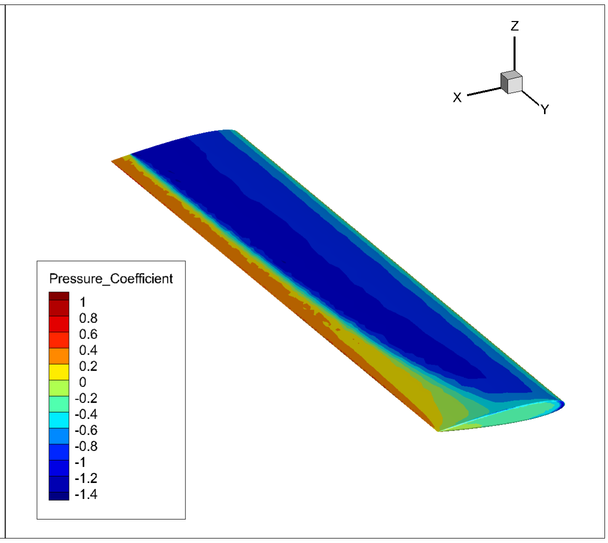


Figure 8: C_p for rigid wing $M_\infty = 0.60$

Figure 9: C_p for rigid wing $M_\infty = 0.85$

The model management strategy is based on observations in Figure (4) and (5). The LoFi model will be implemented in the HiFi analysis for any load increment where the free-stream Mach number does not exceed 0.7. Additionally, the HiFi model will be activated for the final increment regardless of the value of the free-stream Mach number in order the ensure that the solution indeed converges to a HiFi equilibrium.

4 RESULTS

In this section four solution methods are compared for two flight conditions. The first flight condition is high-subsonic flight (Mach=0.6) and the second is transonic flight (Mach=0.85). The high-subsonic case is divided by three load increments and the transonic case is divided by five load increments.

The structural model is an isotropic cantilever beam divided into 10 elements. The structural properties are listed in Table 1. The aerodynamic analysis is considered complete when a sufficient drop in the norm of the residual is observed:

$$\left\|\mathcal{R}_{\mathrm{a}}^{(\mathrm{n})}\right\|_2 < \varepsilon_{\mathrm{a}}\left\|\mathcal{R}_{\mathrm{a}}^{(0)}\right\|_2 \tag{7}$$

where $\varepsilon_{\mathrm{a}} = 1\mathrm{e}^{-4}$. The Newton or Defect-correction iteration is terminated when the displacement increments are sufficiently small:

$$\left\|\Delta\mathbf{u}^{(\mathrm{n})}\right\|_2 < \varepsilon_{\mathrm{s}}\left\|\mathbf{u}^{(\mathrm{n})}\right\|_2 \tag{8}$$

where $\varepsilon_{\mathrm{s}} = 1\mathrm{e}^{-4}$. The processor is 1,7GHz Intel Core i7 and the memory is 8GB 1600MHz DDR3. The analysis is performed on a single core.

E [GPa]	ν	G [GPa]	Width [m]	Thickness [m]
69.00	0.33	25.94	1.000	0.045

Table 1: Structural properties

The number of tetrahedral elements for the CFD model is 405129 and the number of panels is 184 (4 in the chordwise direction and 46 in the spanwise direction).

The first two methods are the Quasi-Newton (QN) method and the Defect-correction (DC) approach as explained in Section 3.1 and 3.2, respectively. The remaining two methods adopt the model management strategy according to Section 3.4 and are denoted QN2 and DC2 for the Quasi-Newton method and the Defect-correction method, respectively. QN2 and DC2 solve the LoFi problem using Newton's method for Mach numbers up to 0.7. When the Mach number exceeds 0.7 the HiFi aerodynamic module is activated to solve the equilibrium equations for the remaining. Regardless of Mach number, the final increment always activates the HiFi solver to ensure a HiFi solution.

Six quantities are of interest for analysing the methods: 1) the tip displacement in the z-direction, 2) the twist angle about the y-axis, 3) the lift coefficient for the aeroelastic deflection, 4) the pitch moment about the mid-chord for the aeroelastic deflection, 5) the total number of HiFi aerodynamic evaluations and 6) the CPU time. The tip displacement and twist angle confirm that the outcome of the four methods are identical (see Table (2) and (3)). The LoFi aeroelastic solution is also included to allow for a comparison of the results. It is evident from Table (2) that the tip displacements for the LoFi and HiFi problems agree well for the subsonic case. The minor difference is due to the thickness effect, visualized in Figures (4) and (5). The most effective method is DC2 followed by QN2.

	Tip disp. [m]	Tip rot. [deg]	C_L	C_M	HiFi eval.	CPU time [s]
LoFi	0.2583	0.4240	0.2935	0.0750	–	140
QN	0.2691	0.4584	0.3121	0.0811	12	4225
DC	0.2691	0.4584	0.3121	0.0811	9	3425
QN2	0.2691	0.4584	0.3121	0.0811	4	1322
DC2	0.2691	0.4584	0.3121	0.0811	3	1087

Table 2: Results for free-stream Mach = 0.60

Although the CPU time corresponds well with the number of HiFi it is not a good quantity for measuring the effectiveness. The CPU time can be improved by means of adjusting the CFL number, adapting the multi-grid or computing in parallel. For this reason, the HiFi evaluations perform somewhat better as a measurement quantity.

	Tip disp. [m]	Tip rot. [deg]	C_L	C_M	HiFi eval.	CPU time [s]
LoFi	1.0228	1.6558	0.5473	0.1419	–	256
QN	0.7692	0.2406	0.4693	0.0026	27	9295
DC	0.7692	0.2406	0.4693	0.0026	23	8790
QN2	0.7692	0.2406	0.4693	0.0026	10	3664
DC2	0.7692	0.2406	0.4693	0.0026	9	3430

Table 3: Results for free-stream Mach = 0.85

A substantial difference in the structural deformations can be witnessed in the transonic case for the HiFi and LoFi problem (see Table (3)). This fact emphasizes the importance and explains why a HiFi aerodynamic model is vital for transonic flow. As in the previous case, major improvements can be made by the implementation of the model management strategy. The additional 6 iterations for DC2 in the transonic case as opposed to the high-subsonic case can be explained by the relatively low quality of the LoFi aerodynamic stiffness matrix. The aerodynamic stiffness matrix is directly linked to the aerodynamic loads. The more the LoFi loads deviate from the HiFi loads, the lower the quality of the LoFi aerodynamic stiffness matrix.

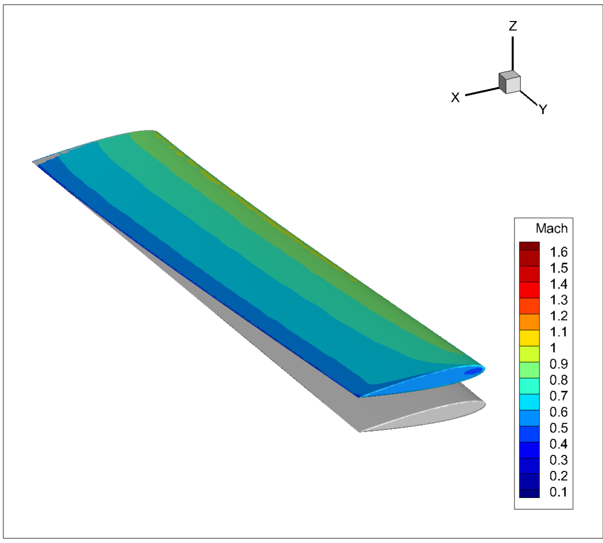


Figure 10: Local Mach for deflected wing $M_\infty = 0.60$

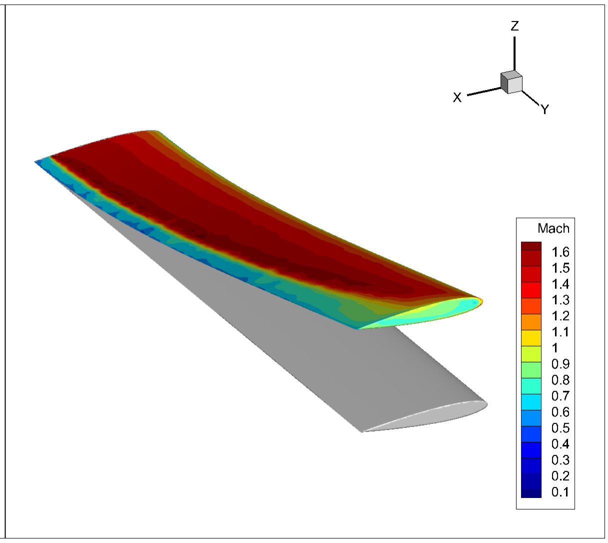


Figure 11: Local Mach for deflected wing $M_\infty = 0.85$

The deformation of the wing can be visualized for the two flight conditions in Figures (10) and (11). The tip deflection for the sub-sonic case is 5.4% of the semispan, indicating that linear beam model would suffice. The use of a non-linear beam model can however be justified for the transonic case where tip displacement exceeds 15.0%.

5 CONCLUSIONS AND FUTURE WORK

An aerodynamic model management framework is presented for the solution of the static HiFi aeroelastic problem. The concept is to utilize the LoFi model in the Mach range where the response from the two models coincides. For high Mach numbers a switch to the HiFi model is activated to obtain a HiFi solution. This results in a significant reduction of the overall computational cost. The Defect-correction method accelerates the convergence compared to the Quasi-Newton method. Investigations of these methods on a more realistic nonlinear structural model will be performed in the near future. Sensitivity analysis is also envisioned in the follow-up paper to allow for gradient-based aeroelastic tailoring.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

[1] Barcelos, M., Bavestrello, H., Maute, K., A Schur–Newton–Krylov solver for steady-state aeroelastic analysis and design sensitivity analysis. *Comput. Methods Appl. Mech. Eng.* 2006, *195*, 2050–2069.
[2] Kennedy, G.J., Martins, J., Parallel solution methods for aerostructural analysis and design optimization, in: *Proceedings of the 13th AIAA/ISSMO Multidisciplinary Analysis Optimization Conference, Fort Worth, TX*, 2010.
[3] Sobieszczanski-Sobieski, J., Multidisciplinary aerospace design optimization: survey of recent developments. *Struct. Optim.* 1997, *14*, 1–23.
[4] Choi, S., Alonso, J.J., Kroo, I.M., Wintzer, M., Multifidelity Design Optimization of Low-Boom Supersonic Jets. *J. Aircr.* 2008, *45*, 106–118.
[5] Balabanov, V., Venter, G., Multi-Fidelity Optimization with High-Fidelity Analysis and Low-Fidelity Gradients, in: American Institute of Aeronautics and Astronautics, 2004.
[6] Jovanov, K., De Breuker, R., Accelerated convergence of static aeroelasticity using low-fidelity aerodynamics, in: American Institute of Aeronautics and Astronautics, 2015.
[7] Katz, J., Low speed aerodynamics, 2nd ed, Cambridge University Press, Cambridge, UK ; New York 2001.
[8] Palacios, R., Alonso, J., Duraisamy, K., Colonno, M., et al., Stanford University Unstructured: An open-source integrated computational environment for multi-physics simulation and design, in: American Institute of Aeronautics and Astronautics, 2013.
[9] Beckert, A., Wendland, H., Multivariate interpolation for fluid-structure-interaction problems using radial basis functions. *Aerosp. Sci. Technol.* 2001, *5*, 125–134.
[10] Beckert, A., Coupling fluid (CFD) and structural (FE) models using finite interpolation elements. *Aerosp. Sci. Technol.* 2000, *4*, 13–22.
[11] Gerbeau, J.-F., Vidrascu, M., A Quasi-Newton Algorithm Based on a Reduced Model for Fluid-Structure Interaction Problems in Blood Flows. *ESAIM Math. Model. Numer. Anal.* 2003, *37*, 631–647.

8 COPYRIGHT STATEMENT