# Aeroelastic Tailoring of Wind Turbine Rotors Using High-Fidelity Multidisciplinary Design Optimization

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## Reviewer 1 Comments and Response

Thank you for your feedback on our work. We break down and address your comments below. Note: Actions taken to address the reviewers' comments are highlighted in red.

The corresponding changes in the manuscript are highlighted in red in the manuscript. Some of the responses to reviewer 2, highlighted in yellow, are also relevant to these comments. Responses to the community comments are highlighted in green.

**Comment 1:** Firstly, the scope of this work is not clear: is it intended as an illustration and first showcasing of the coupled optimization method? If so important details regarding the method's details are missing throughout the paper, and it would be very hard for a third party to reproduce the results showcased with the information contained in the paper.

**Response:** The reviewer correctly identifies the dual scope of this work. We agree that this should be made more explicit in the text. Necessary clarifications have been added to Sect. 1.2.

Regarding the replicability of the results, both the wind turbine model and the framework we use have been extensively described in detail in the literature. Although we did not upload the input files of our model on a public repository, we would be happy to share them with the interested reader. A sentence about data availablility has been added at the end of the manuscript. The benchmark turbine we use as a reference is available on the official DTU GitLab repository. We discuss the assumptions of our model and the differences from the original configuration in Sect. 3. The publicly available components of the MACH framework are referenced in the footnotes, and several literature references are provided for individual components and overall framework applications. Moreover, NASA's fully open-source MPhys framework provides comparable aerostructural optimization capabilities using both MACH solvers and other well-known CFD tools. Considering that the definition of the benchmark we studied in this work is publicly available, and the open character of the software we used, we believe this study is replicable.

**Comment 2:** On the other hand, if the objective is to discuss the results of the optimization discussed in the paper, various corners appear to have been cut: the blade is made of aluminum and no details regarding how the distribution along the blade of the various thickness panels is chosen is given

**Response:**

For the distribution of the various thickness panels, we subdivided the blades following the main geometrical features of the planform. We further clarified the process in Sect. 3.

We acknowledge that our model has modeling limitations and we are actively developing an updated structural model that will address these concerns. We aim at presenting new results for aerostructural optimization using anisotropic composite materials at the WCSMO 2023 conference and a following journal publication.

The assumption of isotropic material properties is necessary at this stage of development. Aluminum properties have been selected for convenience and can be changed at runtime in our scripts. We stress again that this is a demonstration of the capabilities of the tool at the current stage, and several previous works with MACH have discussed optimizations of composite wingboxes [1].

The ongoing effort mentioned above will also use a more refined parametrization both along the span and the blade section.

**Comment 3:** From an aerodynamic perspective, no mesh convergence & important details on model set-up are presented, and baseline results are not compared to other author's predictions for this testcase.

**Response:** The aerodynamic mesh and solver are the same as the ones used by Madsen et al. [4]. That work presents a grid convergence study and a comparison with DTU's Ellypsys CFD solver, extensively discussing the pros and cons of the two tools. We ensured that our aerodynamic simulations match the values from the previous study, but chose not to add a section for the sake of conciseness. As more readers might be looking for the same information, we extended the discussion to redirect them to Madsen et al. [4] for more details.

**Comment 4:** Moreover, the single-point optimization, without accounting for extreme loads in other operating and parked conditions is questionable, and the authors also acknowledge this in the paper.

**Response:** We acknowledge that the sizing and design of this turbine are not to be intended as a reference for practical applications, as we focus on the capability demonstration of our code. We explicitly investigate the performance of the blade at below-rated conditions as our framework does not include turbine controls or dynamic simulation capabilities.

Academic work and industry practice demonstrated how single-point optimizations exploit geometrical and structural features for the specific design point, often at the detriment of the performance over the rest of the operational envelope [3]. Two separate works will address this limitation. On the one hand, we are investigating a different multipoint optimization problem formulation that includes site-specific considerations. We aim to present the study at the WESC 2023 conference and a following publication. On the other hand, we are actively working to extend the study started in [2] to enable constraints for extreme and fatigue loads in our high-fidelity optimization framework. Results will be discussed in a separate publication.

We made these points more explicit in Sects. 1.2 and 4.4.

**Comment 5:** Title: "Aeroelastic Tailoring": What is the reasoning for including this term in the title? Perhaps consider elaborating on the concept of aeroelastic tailoring and what it means in the context of this study when discussing results in section 5.2.

**Response:** We agree on this point. Aeroelastic tailoring is now discussed in Sect. 5.2 and 5.3

**Comment 6:** Literature review: An interesting concept that I don't think was considered in the literature review is to use high-fidelity simulation to train a meta-model such as an Artificial Neural Networks (ANN) to perform design exploration, such as proposed by (Lorenzo Cozzi et al 2022 J. Phys.: Conf. Ser. 2265

042050). The best candidate designs can then be simulated, and the ANN can be updated and the process repeated if needed.

**Response:** The authors are aware of the mentioned paper, which presents a promising methodology in the field of wind turbine design optimization. However, we feel that such a methodology differs significantly from what we propose in our work. A more extensive literature review including optimization through meta-models would increase the length of this manuscript without adding information useful for the reader to better frame our research. Therefore, we mention the work in Sect. 1.1 but we choose to leave further discussion out of the literature review presented in this manuscript.

**Comment 7:** Figure 1: This illustration is very detailed, but it is hard to read. My suggestion is to move it to an appendix and focus on a more streamlined and simple illustration here. Moreover, the differences between the loosely-couple and tightly-couple aero structural optimization loops should be investigated.

**Response:** We agree on the need to make the XDSM diagram easier to read. We removed unnecessary components from the diagram and increased the size of the figure. We also refer directly to the XDSM components in the framework description in Sect. 2 Moreover, we added clarifications in Sect. 5.1 to help the reader understand the differences between the two approaches. As for the loosely coupled approach, we added a simplified XDSM diagram to the manuscript. Together with Algorithm 1, it should help to clarify the differences between the two optimization strategies.

**Comment 8:** Section 3: No details regarding boundary conditions, problem formulation, turbulence model and numerical domain are given. Moreover, authors state that various meshes are tested, but no comparison between them is presented. The choice of L1 mesh makes sense to reduce core-hours but does it ensure high enough accuracy?

**Response:** We use the Spalart–Allmaras turbulence model for this work, as mentioned in Sect. 2. The details of the boundary conditions, problem formulation, and numerical domain are detailed by Madsen et al. [4] We added some high-level details and explicitly directed readers to that previous work for this information. This previous work also details a thorough grid convergence study and uses both L1 and L0 meshes. As discussed by Madsen et al. [4], ADflow overpredicts the loads on the L1 meshes; but preserves the same features and load trends. The comparison of baseline and optimized layouts in Fig. 1 highlights this behavior. This figure was not added to the manuscript for sake of conciseness. Therefore, we expect the results of an optimization with L0 to be consistent with those based on L1. With the resources available for this study, an optimization with L0 was numerically untractable.

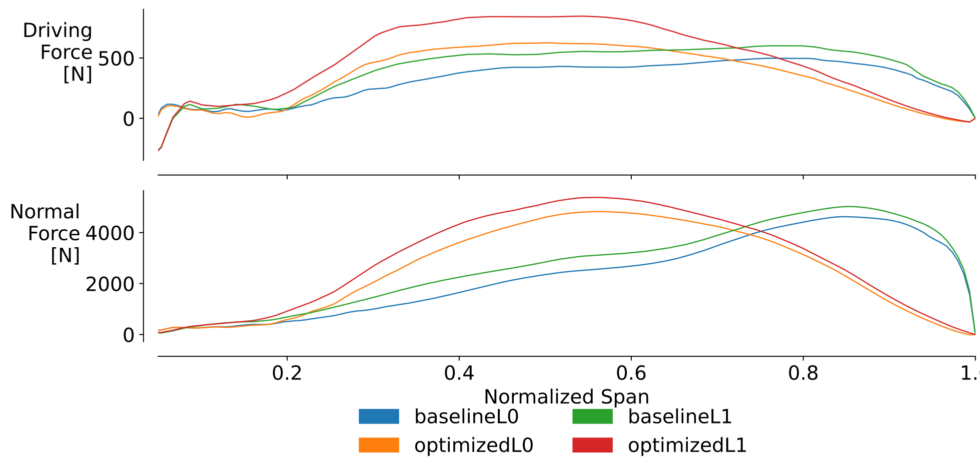


Figure 1: Aerodynamic loads for the baseline and the optimized rotor. For each rotor, the load distributions are computed with the L1 and the L0 mesh. Both the normal and the driving forces are overpredicted with the L1 mesh, but the load distributions remain consistent with the L0 results.

**Comment 9:** Section 3: It is not clear to me how the structural problem is formulated. Is it a static analysis? Is it possible to account for complex aeroelastic interactions with the methods (flutter, vortex-induced vibration, etc...)

**Response:** We run a static analysis of the structural model under steady aerodynamic loads, so dynamic instabilities are outside the scope of this study. We clarified the structural setup in Sect. 3

**Comment 10:** L463: ". The discontinuities in the plots originate from minor inconsistencies in the location of leading and trailing edge points at consecutive airfoil sections because we extract these distributions directly from the deflected aerodynamic meshes of the coupled solution" - I think this needs to be explained better. Without further information I would not expect differences in local deformation to lead to discontinuities in twist as seen in Figures 5 and 6.

**Response:** We updated the explanation in the manuscript. The noise in the twist distribution is not due to local deformation, but to a non-deterministic behavior when ADflow identifies the surface mesh nodes associated with the leading and trailing edges. From one section to the next, the locations identified as LE and TE can switch between the discrete collection of airfoil mesh nodes. Since the twist is defined as the angle between a reference line and the chord line (connecting LE and TE), even small perturbations of these points lead to the discontinuities shown in the plot. This limitation in ADflow postprocessing will be addressed in future work.

**Comment 11:** Figure 6: It is not clear to me what is being shown here. What is the difference between the "Rigid" and flexible cases? Is it the difference caused by the blade deflection or is it a different starting geometry?

**Response:** We updated the manuscript and the caption to clarify this point. We now use "deflected" and "undeflected" to avoid confusion. "Rigid" refered to the undeflected blade shape on which the geometry deformations are applied. The other case refers to the same blade deflected under the aerodynamic loads at the prescribed inflow conditions we use in our optimization. This figure displays how the twist distribution changes when loads are applied to the blade, highlighting how the optimizer accounts for passive load alleviation in the design process.

## References


[1] Timothy R. Brooks, Joaquim R. R. A. Martins, and Graeme J. Kennedy. Aerostructural trade-offs for tow-steered composite wings. *Journal of Aircraft*, 57(5):787–799, September 2020.

[2] Denis-Gabriel Caprace, Adam Cardoza, Andrew Ning, Marco Mangano, Sicheng He, and Joaquim R. R. A. Martins. Incorporating high-fidelity aerostructural analyses in wind turbine rotor optimization. In *AIAA SciTech Forum*, January 2022.

[3] Mark Drela. *Frontiers of Computational Fluid Dynamics*, chapter Pros and Cons of Airfoil Optimization, pages 363–381. World Scientific, Singapore, November 1998.

[4] Mads H. Aa. Madsen, Frederik Zahle, Niels N. Sørensen, and Joaquim R. R. A. Martins. Multipoint high-fidelity CFD-based aerodynamic shape optimization of a 10 MW wind turbine. *Wind Energy Sciences*, 4:163–192, April 2019.