RAPTOR: a gradient-based multidisciplinary design optimization framework for aircraft preliminary design

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ABSTRACT

Early-stage aircraft design has traditionally relied on iterative design methodologies, characterized by a weak coupling between the various aeronautical disciplines. While these approaches have proven effective for the development of conventional aircraft configurations and have been successfully applied for decades, they become increasingly time-consuming and less suitable when addressing unconventional designs. Multidisciplinary Design Optimization (MDO) offers a powerful alternative by enabling a simultaneous and consistent coupling between disciplines within an automated design workflow. This paper introduces RAPTOR (Rapid Aircraft Preliminary Optimization and Refinement) [1], an open-source, Python-based multidisciplinary design and optimization framework built on top of OpenMDAO [2]. The framework is designed to support modular and multi-fidelity analyses through a broad set of validated and interchangeable models. A gradient-based optimization strategy is adopted in RAPTOR to efficiently address constrained optimization problems involving large numbers of design variables. As the models integrated within the framework typically require numerous input parameters, a correspondingly large number of derivatives is needed for gradient-based optimization. Computing these derivatives analytically would be prohibitively time-consuming, and therefore, model sensitivities are primarily evaluated using algorithmic differentiation. This capability is fully automated within RAPTOR, enabling seamless differentiation of any continuous model integrated into the framework. The overall optimization workflow has been validated through the successful reproduction of several reference optimization cases from the literature, including the tailless UAV optimization case proposed by Kim et al. [3]. This case was reproduced within RAPTOR, and a detailed comparison of the obtained results is documented by Van Den Berghe [1].

Within the framework, aircraft geometry parametrization is handled through a dedicated interface with OpenVSP [4]. Aerodynamic analyses are performed using both empirical models and physics-based formulations relying on the SDPM (Source Doublet Panel Method) [5]. The framework further includes weight estimation models, combining CAD-based approaches derived from OpenVSP with analytical formulations. Modules for aircraft equilibrium and stability analysis are also implemented, using empirical relations as well as SDPM simulations. Structural calculations rely on an analytical model, and empirical performance assessment capabilities are additionally available in the current version of the software.

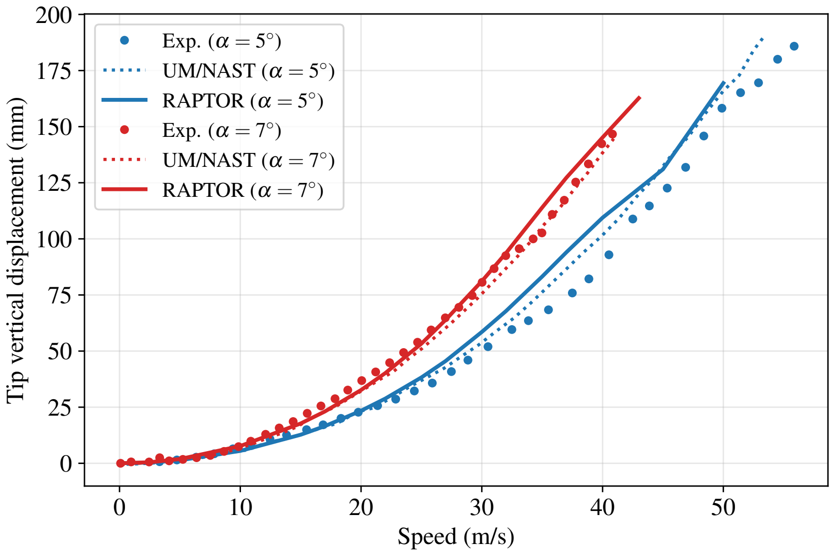

Figure 1: Pazy wing static aeroelastic response: wing-tip leading-edge vertical displacement as a function of the freestream velocity for $\alpha = 5°$ and $\alpha = 7°$, comparing experimental measurements and RAPTOR predictions.

The next major capability currently being implemented within the framework is the aerostructural analysis module. In this formulation, the aerodynamic and structural models are coupled through an iterative loop, where aerodynamic loads are computed using SDPM, structural responses are evaluated with TACS [6], and load and displacement transfers between non-matching aerodynamic and structural meshes are performed using the MELD [7] scheme, part of the FUNtoFEM [8] framework. The overall aerostructural solver assembly and non-linear block Gauss-Seidel (NLGBS) strategy are handled through an MPhys [9] interface. The aerostructural analysis capability of RAPTOR is validated by reproducing the benchmark case of the Pazy wing, which was originally introduced for the validation of aeroelastic models [10]. This test case is characterized by a highly flexible structure, leading to significant static deflections under aerodynamic loading. The wing consists of a thin aluminum spar, a Nylon 12 additively manufactured rib chassis, and a polyester film skin [10], and features a NACA 0018 airfoil. Experimental reference data are taken from the Technion Test 2 wind tunnel campaign [10]. The same test case was also reproduced by Cesnik and Riso using the UM/NAST software [11]. In this work, UM/NAST relies on a low-order, geometrically nonlinear aeroelastic formulation combining a strain-based beam structural model with strip-theory aerodynamics, complemented by a calibrated tip-loss correction to account for three-dimensional effects, as detailed by Riso and Cesnik [11]. The static aeroelastic response is analysed for two angles of attack, considering freestream velocities ranging from 0 to 56 m/s at 5° and up to 43 m/s at 7°. The quantity of interest is the vertical displacement of the wing-tip leading edge as a function the freestream velocity. The structural model is adopted from the work of Riso and Cesnik [11]. Numerical predictions are compared against experimental measurements and are presented in Figure 1. Overall, the results show good agreement with the experimental data, both for RAPTOR and UM/NAST with improved accuracy observed at an angle of attack of 7° compared to 5°. The remaining discrepancies are limited and can be attributed to modeling assumptions, such as the inviscid nature of the aerodynamic formulation. These results illustrate the validity of the aerostructural model implemented within RAPTOR.

To further demonstrate the capabilities of the proposed framework, the full paper will present the results of a multidisciplinary optimization applied to an aircraft configuration. The optimization problem focuses on the minimization of aerodynamic drag, subject to stability, equilibrium, and structural constraints, and is formulated in line with established aerostructural optimization studies reported in the literature [12, 13]. The set of design variables includes the main wing geometric parameters, the internal wing structural properties, the aircraft angle of attack, and the horizontal tail incidence. Aircraft geometry is generated through the coupling between RAPTOR and OpenVSP. Component weights and centers of gravity are evaluated using geometry-based models developed within the framework, while the wing structural mass is computed using TACS. Equilibrium and stability analyses are performed using dedicated RAPTOR modules based on SDPM, and the previously validated aerostructural model is fully integrated into the optimization process. Finally, the full paper will extend the aerostructural model to dynamic aeroelasticity by introducing a flutter analysis capability, validated on the Pazy wing configuration.

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