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Towards multidisciplinary design optimization of next-generation green aircraft

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Abstract. Reducing greenhouse gas emissions is one of the most important challenges of the next future. The aviation industry faces increasing pressure to reduce its environmental footprint and improve its sustainability. This work is framed within the Italian national project “MOST- Spoke 1 - AIR MOBILITY - WP5,” which studies innovative solutions for next-generation green aircraft. This paper proposes a multidisciplinary design optimization (MDO) framework for the design of new-generation green aircraft. Several propulsion solutions are analyzed, including fully electric and hydrogen fuel cells. The Multidisciplinary Design Optimization (MDO) framework considers several disciplines, including aerodynamics, structures, flight dynamics, propulsion, cost analysis, and life-cycle analysis for facing at the best the design challenge of next-generation green aircraft.

Introduction

For developing new-generation green aircraft, it is important to consider the interactions between the system’s disciplines. Through early resolution of the multidisciplinary optimization (MDO) problem using state-of-the-art computational analysis tools, it is possible to enhance the design while concurrently minimizing the time and cost associated with the design cycle. In the realm of developing next-generation environmentally friendly aircraft, while the Maximum Take Off Mass (MTOM) remains a conventional optimization objective due to its strong correlation with the overall lifecycle cost of the aircraft, it is crucial to conduct a thorough-life cycle analysis and establish a metric for assessing the aircraft's overall environmental sustainability. Accurately modeling new-generation environmentally friendly propulsion systems and establishing a merit function for comparing the environmental friendliness of aircraft, such as the total equivalent CO2, is crucial. In addition to traditional disciplines like aerodynamics, structures, and flight dynamics, green propulsion system modeling and life cycle analysis are essential, even in early design stages. This study provides an overview of physical-based models for structural analysis, aerodynamics, green propulsion systems, and life cycle analysis for preliminary design. Moreover, a Multi-Disciplinary Optimization (MDO) architecture is presented, including considerations of Design Variables (DVs), constraints, and objective functions.

Structural modeling

Structural models are essential for optimizing aircraft performance, efficiency, and safety. They must withstand different loads and conditions while being lightweight to maximize range, payload capacity, and minimize operating costs. Various low fidelity structural models are used for aircraft optimization, such as analytical beam models. Beam models efficiently represent elongated components like wings, fuselages, and tails, considering bending, shear, torsion and axial loads. They provide insights into stress distribution, deflections, and dynamic response, assuming linear elasticity, small deflection theory, and homogeneous materials. Beam models are valuable for preliminary design, concept exploration, and rapid evaluation of structural configurations. However, with enhancements in computational capabilities, Finite Element Models (FEM) have gained popularity in aircraft optimization due to their versatility and accuracy. Moreover, FEM allows for a more detailed analysis of complex geometries. It is particularly beneficial for innovative aircraft configurations such as, for example, the blended wing body, and truss braced wings. In this work, a FEM model of the entire aircraft is generated using an in-house code called FUROR (Framework for aUtomatic geneRatiOn of aeRoelastic models) based on the input of assigned set of design variables. FUROR utilizes the open-source geometric library OpenCasCade to automatically generate the wing boxes and fuselage geometries, and the open-source code GMSH for automatic FEM grid generation. The generation of the aircraft FE model involves three steps. First, the aircraft geometry is defined based on main standard geometrical characteristics such as wingspan, dihedral, sweep, chord, and fuselage length (see Fig. 1). Additionally, the geometry of the main structural components, including wing spars, ribs, and stringers, is also defined. In the second step, a hybrid structured-unstructured FEM mesh is generated using GMSH. Finally, the complete FE aircraft model is generated, where the beam sections and shell thickness of the FEM model are defined in a standard Nastran input file. Furthermore, during this phase, the connections between the wings and the fuselage are established using a simplified approach that is compatible with the early design stage. Additionally, FUROR has the capability to generate the aerodynamic wing model, which will be discussed in detail in the following section.

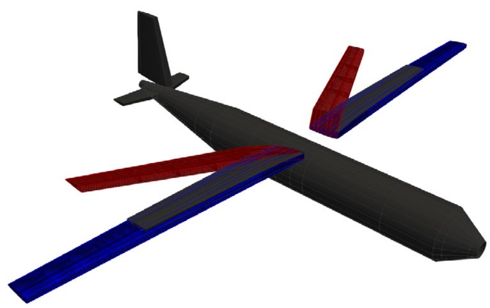

Fig. 1: Generation of FE aircraft models with different main standard geometrical characteristics. In grey a standard regional aircraft, in blue an increased wingspan design and in red an increased wing sweep design.

Aerodynamic modeling

Aerodynamic modeling is crucial in the preliminary design for evaluating forces and mission performance. Various models exist with different accuracy and computational cost. Simplified physical-based aerodynamics models such as strip theory, doublet lattice, or vortex lattice methods are crucial in the field. Strip theory divides the wing into sections, evaluating the local angle of attack for each. Lookup tables determine each segment's lift and drag coefficients and the corresponding aerodynamic forces. A correction factor is applied for three-dimensional effects, and the Theodorsen method can be used for unsteady aeroelastic dynamic analyses. Strip theory enables the estimation of aerodynamic efficiency with drag estimation, also approximately incorporating viscous effects. However, strip theory lacks accuracy in estimating three-dimensional effects and wing interactions because simple analytical models are typically used in such cases. In preliminary design, the doublet lattice method is commonly employed as a three-dimensional model. It offers enhanced accuracy in lift evaluation, making it suitable for aeroelastic analysis and accounting for finite wake effects. In the FUROR software, both the strip theory approach and the doublet lattice method are available.

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Propulsion Modeling

The proposed model for the propulsive system is based upon the work of De Vries et al. [1]. Authors aimed to propose a simple method for evaluating the benefits and technological needs of integrating a secondary energy source (batteries or fuel cells) with the primary thermal source (fuel) in the redesign of an existing aircraft. In this method, the various configurations are characterized by the supplied power ratio, which represents the ratio between the power output from the batteries and the total power output, taking into account the electric subsystem and the fuel. The proposed method combines constraint analysis, mission analysis, and subsequent aircraft mass estimation. The first step involves a classical constraint analysis that aims to meet all mission requirements by utilizing an aircraft propulsive power constraint diagram.

From this diagram [1], a specific design point is selected based on the power-to-weight ratio (P_p/W_{TO}) and wing loading (W_{TO}/S). Then, the next step consists of quasi-stationary mission analysis to size the aircraft in energy terms, having chosen a first attempt MTOM. A simplified mission profile is selected, consisting of different flight phases. Various authors [2,3] have derived analytical formulas similar to the Breguet equation or modified it for hybrid aircraft, but these formulas depend on the aircraft configuration, and there is no universally optimal choice. The presented design method explores different approaches for using battery and fuel in specific flight phases. The energy requirements from both fuel and battery sources are integrated over the entire mission duration. In the final phase, the aircraft's masses are estimated, including energy sources and propulsion system components. From these mass estimates and the mass outcomes of the structure subsystem, MTOM is derived, which corresponds to the energy required by the two energy sources to complete the mission. The last two steps of the method are iterated until the MTOM value of two consecutive iterations converges below a certain chosen tolerance. Lastly, a basic life cycle analysis should be conducted to estimate the total CO2 emissions. This analysis considers not only fuel emissions from gas turbine engines but also battery discharge for hybrid/full-electric aircraft, as well as the production and transportation of aircraft components. This approach ensures a fair comparison among the proposed configurations.

Multidisciplinary Design Optimization

The initial stage of aircraft design involves establishing the Top-Level Aircraft Requirements, e.g., desired overall performance, capabilities, and main characteristics of the aircraft. Traditionally, the optimization objective has focused on the Maximum Take Off Mass (MTOM) due to its close relationship with the overall lifecycle cost of the aircraft. A thorough life cycle analysis is crucial in developing eco-friendly aircraft to evaluate overall environmental sustainability. After defining the objective functions, the next step involves selecting the DVs and determining their ranges. Both structural and shape variables must be employed. Structural variables primarily focus on minimizing weight, while shape variables contribute to the optimization of aerodynamics which is of the utmost importance for the propulsion design to the evaluation of the energy requirements. Finally, to fully address the MDO problem, constraints need to be defined. This includes considering mission constraints such as range and altitude, conducting a stress assessment for extreme maneuver load cases to ensure aircraft safety, and incorporating constraints directly related to the propulsion system such as take-off distance and the estimated specific energy for the batteries and fuel cells that will be introduced in the weight estimation process. The design space can be systematically investigated by an optimizer (a possible choice is the Multi Objective Genetic Algorithm) to uncover the Pareto front of the selected objective functions (MTOM and total equivalent CO2). When the complete multidisciplinary analysis (MDA) is executed for every set of DVs, the MDO framework is referred to as Multi-Disciplinary Feasible (MDF) architecture [4]. This ensures the feasibility of each discipline for every set of DVs. The MDA involves conducting a trim and static structural analysis for various extreme maneuver load cases, followed by an aeroelastic analysis to ensure sufficient aeroelastic damping during maximum aircraft speed conditions (see Fig. 2). Additionally, the constraint and mission analysis are carried out to estimate the required battery pack (or fuel cells) mass necessary to accomplish the TLARs. Finally, the life cycle analysis is performed. To handle interdependencies among disciplines, an iterative approach is used, ensuring convergence of the MDA by matching the disciplines' output copy with the final output.

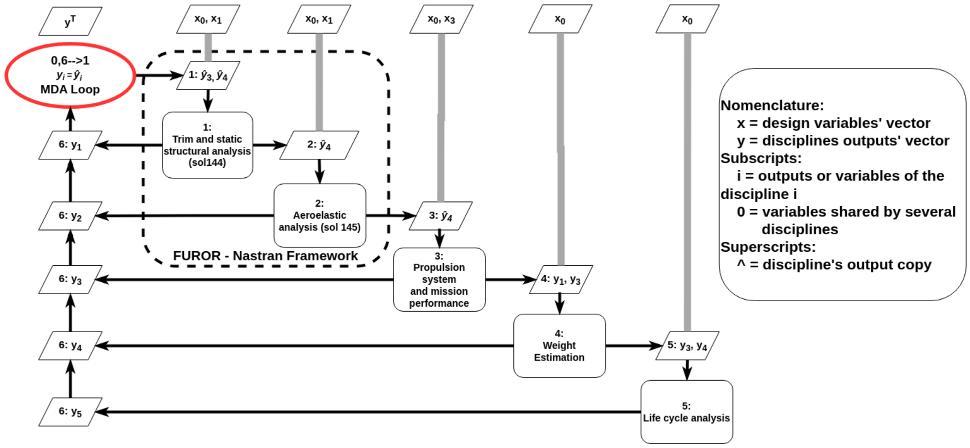

Fig. 2: Multi-Disciplinary Analysis Extended Design Structure Matrix [4]

Conclusions

This work presents an MDO architecture for advanced green aircraft, outlining the objective function, constraints, and design variables. Additionally, it describes the reduced order models (ROMs) for each discipline with appropriate fidelity for early design. The subsequent phases involve implementing the proposed MDO framework and conducting optimization on a reference regional aircraft, exploring various propulsion systems and innovative configurations (e.g., blended wing body, truss braced wing).

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