HiSST: 3rd International Conference on High-Speed Vehicle Science Technology

14 -19 April 2024, Busan, Korea

Conceptual Design and Multi-Objective Optimization of an Environmentally-Friendly High-Speed Civil Aircraft

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Abstract

An aircraft design framework is developed and employed for the optimization of a Mach 1.6, 7000 km range, 72-passenger aircraft, to minimize aircraft weight, cost, emission, and noise. To this aim, the aircraft configuration is designed, and a base layout is developed using rapid engineering methods and area ruling requirements. This base layout is then optimized in the developed framework concerning weight, cost, emission, and noise objectives. The core disciplines of the optimization framework are Requirements, Weight, Sizing, Geometry, Aerodynamics, Engine, Performance, Cost, Emission, Noise, and Optimization. High-fidelity CAD and FEA processes are used to loft the aircraft's external surface and estimate the wing weight, respectively.

Keywords: Civil Aircraft, High-Speed Transport, Optimization, Conceptual Design, MDAO

Extended Abstract

Since the early 1970s and according to the Federal Aviation Administration regulations, the supersonic flight of civil aircraft over land is prohibited due to noise issues. Despite this limitation, supersonic transport for civil purposes is being strongly investigated in academic and industrial sectors. There is a new wave of research from the beginning of the 21st century to address these issues, and to develop a feasible and profitable aircraft [1]. The supersonic transport will bring new potential to the transport market due to their higher speed, with a potential to be time-saving. This time-saving can benefit the business jet market [2]. On the other hand, for a successful entry into the market, the aircraft should be economically efficient and environmentally friendly.

In the conceptual design phase, different aircraft configurations are investigated. In this design phase, the configuration is so fluid that even the topology of the aircraft is allowed to change. For this reason, and to keep this agility and flexibility affordable, the fidelity of the aerodynamics and structural analysis tools is kept low [3]. Furthermore, the details that are considered in this phase are limited. But with the new requirements and considering the cost and emissions, it is important to develop tools and methods that are capable of design and optimization of aircraft with high-fidelity methods, even at the conceptual design phase.

On the other hand, the conceptual design and optimization of novel configurations require the integration of many disciplines (such as weight, aerodynamics, propulsion, performance, cost, emission, and noise) into a unified design framework. Depending on the configuration, the design framework should be capable of capturing the underlying physics of one or more disciplines, when no statistical or historical data is available. To overcome this issue, the design framework should be capable of both handling low-fidelity empirical and high-fidelity analysis tools [4].

In this research, an existing framework for subsonic and transonic civil aircraft conceptual design and optimization is extended to cover the design and optimization of high-speed supersonic civil aircraft. The framework is developed in MATLAB, and it compromises a modular architecture, which gives the potential for using different methods for each discipline.

The core disciplines of the optimization framework are (see Fig 1): Requirements, Weight, Sizing, Geometry, Aerodynamics, Engine, Performance, Cost, Emission, Noise, and Optimization. The requirements

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module processes the top-level aircraft requirements, which are defined by the user, and develops the requirements data structure according to the regulation. The developed framework contains both statistical-based methods (empirical) and physics-based methods (low-fidelity and high-fidelity simulations). A set of codes is developed in MATLAB to transfer the data between the modules, iterate the convergence and optimization process, pre-processing the inputs, and post-processing the results. The code input is a text file, and its outputs are plots and the design results stored in local files. Since all required information, inputs, and options are defined inside the input file before the execution of the code, there would be no interaction with the user during the code processing. This file-based approach is selected over the interaction-based approach to reduce computational time and provide batch processing capability.

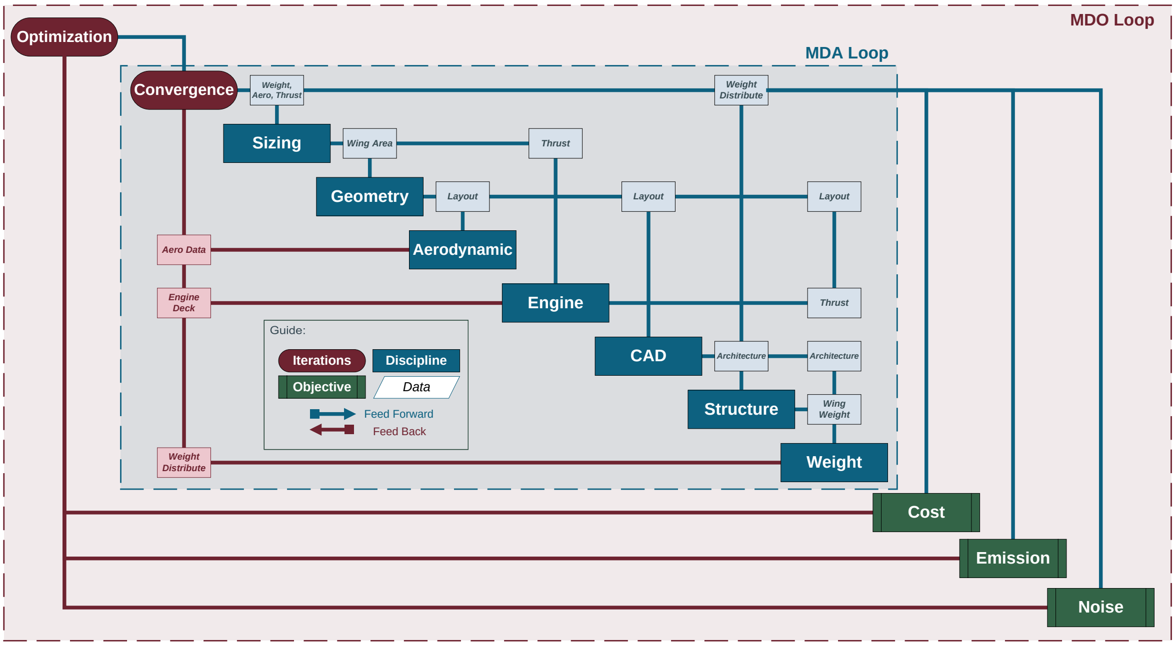

Fig 1. Optimization Framework Flow Chart

These requirements are used to estimate the initial values of the aircraft weight at the next step. At the initial design stages, statistical methods are used to estimate the weight of the aircraft. In the next steps, empirical methods that rely on aircraft geometry and mission are used for component weight estimation. At the final stages of the design, as the aircraft configuration does not undergo major changes at each design iteration, a high-fidelity method will be used. In this method, the structural primary weights are estimated by finite element analysis. The loads are developed from aircraft mission requirements.

In the next process, the required wing area, engine thrust and tail areas are computed based on the regulatory and technical requirements. The output data of this module is used for the development of the aircraft geometry. In this step, engineering methods are used to develop the geometrical layout where no input is provided by the user. By using CAD parametric modeling rules, a 3D aircraft model is created considering area ruling requirements, and this model can be used by higher-fidelity methods such as the FEM and CFD. The wing geometry, including the external surfaces and structure architecture, is extensively parametrized using knowledge-based engineering rules within a high-fidelity and industry-standard CAD tool. The application of parametric and associative modeling rules enables the possibility for fast geometry and structure architecture updates. This implementation covers both updating the existing geometrical elements (e.g., changing the wing spar location) and the creation and deletion of structural elements (e.g., adding or removing ribs depending on the wing span).

The aerodynamics analysis is carried out at different levels of fidelity. At the initial design stages, engineering and potential methods are used, while at later stages, higher fidelity CFD methods are used. The process of converting the CAD model into computational mesh, performing the aerodynamic analysis, and post-processing the results are carried out by dedicated scripts, which finally feed the drag polar into the performance module. In addition, a module is developed which generates the engine deck according to the scaling methods.

Because of the structural configuration of novel aircraft, which may be different from the existing aircraft and therefore, lack of statistical data, it is essential to have the capability to use a high-fidelity method for the calculation of structural weight. In addition, with current advances in computers and computation parallelization, more research is focused on the application of high-fidelity methods for the calculation of weight [5]. A new method is developed, and subsequently employed to calibrate the wing weight estimation module in the sizing and optimization loop. In this process, the finite element method is used to size the load-carrying structures and estimate the secondary weights using empirical methods. The external wing loads are extracted by filtering from hundreds of load cases, from which the most critical load conditions are used for the sizing process. In the loading process, variations in weight, center of gravity, speed, altitude, and throttle levels are considered. The rapid engineering methods are used for the estimation of aerodynamic load distribution along the wing span. In addition, the weight is distributed along the wing span, and discrete loads such as engine thrust and engine weights are also considered. Based on the developed wing geometry and calculated loads, the wing finite element model using shell and beam elements is created automatically by Visual Basic scripts. For strength sizing, the shell model and applied loads are used to find the optimum structural weight. The computed optimum wing is used along with the secondary items' weight to estimate the wing's structural weight.

At the performance module, the required fuel for the accomplishment of the mission is computed. In this process, instead of using simple fuel fraction methods, the equations of motions are solved at each time step the trim condition is determined and the fuel flow is computed accordingly.

A surrogate optimization methodology based on the Design of Experiment (DoE), Neural Network (NN), and Genetic Algorithm (GA) is implemented to find the results. The overall scheme of this framework is presented in Fig 2.

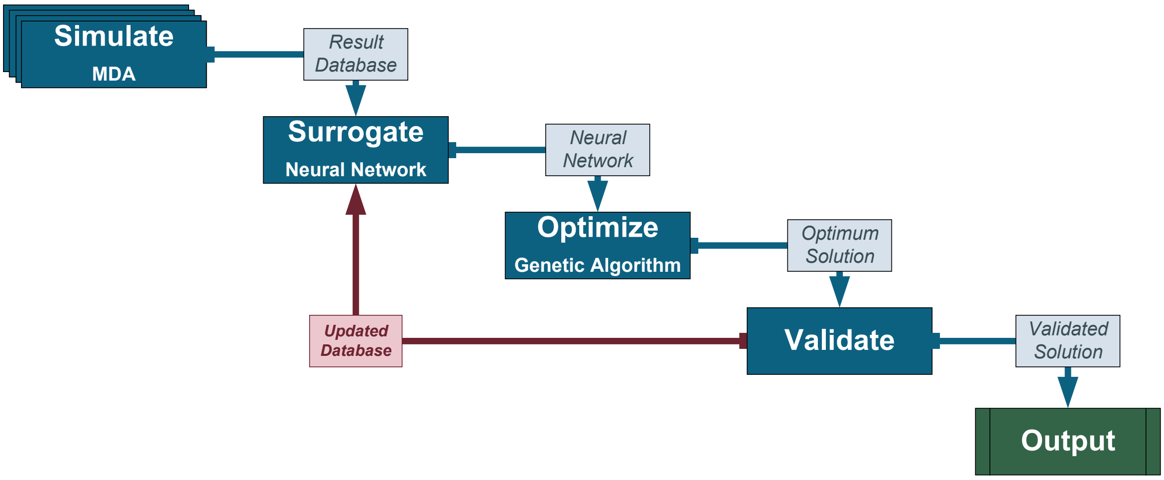

Fig 2. Variation of Forcing Factors with Altitude

A population of samples is randomly generated using the Latin Hypercube method, and these samples will be used to populate the database. Each set of design variables is used in the MDA process, and the objective functions are calculated. The Neural Network (NN) method is implemented to create and train a surrogate model. This surrogate model is used to guess the objective function based on any set of desired design variables. The network has one hidden layer and 50 neurons. A Genetic Algorithm (GA) is then used to find the optimum solution by using the developed surrogate NN model. Since the design framework is developed in MATLAB, existing functions and toolboxes from MATLAB are used for NN and GA, and auxiliary functions and codes are added to pass the information to these modules.

The developed framework is employed for the optimization of a Mach 1.6, 7000 km range, 72-passenger aircraft, to minimize aircraft weight, cost, emission, and noise. To this aim, the aircraft configuration is designed, and a base layout is developed using rapid engineering methods and area ruling requirements. This base layout is then optimized in the developed framework concerning weight, cost, emission, and noise objectives. The optimized aircraft are discussed, and the Pareto front is analyzed.

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