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Multidisciplinary design optimization of commercial airplane wing based on Aerodynamic and structure

Amirfarhang Nikkhoo[1], Ali Esmaeili[2*]
1-MSc aerospace engineering student, Engineering Faculty, Ferdowsi University of Mashhad, Email: amirfarhang.nikkhoo@mail.um.ac.ir
2- Assistant professor, Mechanical engineering department, Engineering Faculty, Ferdowsi University of Mashhad, Iran, Email: aliesmaeili@ferdowsi.um.ac.ir

Abstract
Aircraft wing design using Multidisciplinary Design Optimization (MDO) techniques is a complex task which involves different disciplines, mainly aerodynamic and structure. The multidisciplinary feasible (MDF) method is a new MDO approach and it involves solving a single optimization problem that calls a multidisciplinary analysis (MDA) when objective or constraint values are required**.** this paper is to optimize the range of a regional jet aircraft using a monolithic MDO technique Multidisciplinary Feasible (MDF). Thus, this research optimized the Bombardier CRJ700 wing and maximization of Breguet range was chosen as objective function and two design variables, as spare thickness from structure part and twist angle from aerodynamic part, were mentioned. Finally, the results demonstrated that the flight range was sharply increased around 41%.

Keywords: ***Optimization – MDO – Aerodynamic - Structure***

1. Introduction

The aeronautic industry faces the considerable challenge of reducing the environmental impact caused by air travel, namely in terms of gas emissions and noise. For instance, the requirements stated in the Flightpath 2050 vision for European aviation[1] are quite challenging and have become design drivers in future aircraft development. Since other important key factors such as life-cycle cost including operations and maintenance must also be satisfied, the greening requirements must be incorporated right from the beginning of the design cycle[2].
Due to the incompatible nature of the goals of environmental impact increase and reduction of speed and capacity, the approach should be the introduction of aircraft multidisciplinary optimization in the design process and the ability to adapt the aircraft to each situation, in order to combine the best possible performance with the minimum environmental and economical impacts.
Concurrently, technological developments in materials and computer sciences have evolved to the point where their synergistic combination has culminated in a new field of multi-disciplinary research in adaptation. Advances in material sciences provide a comprehensive and theoretical framework for implementing multifunctionality into materials, and the development of high-speed digital computers has permitted the transformation of that framework into methodologies for practical design and production. Adaptive structures represent a new approach or design philosophy that integrates the actions of sensors, actuators and control circuit elements into a single system that can respond adaptively to environmental changes in a useful manner.
From the time of the first fliers, aviation engineers have sought an aircraft that will generate the maximum lift with the minimum drag. The relentless search for such an aircraft led to the creation of the flying wing (FW) concept. A FW aircraft is an aircraft without empennage and a fuselage; the entire payload is located inside the wing**.**
Flying wing configuration has been considered as an ideal configuration of the future unmanned aerial vehicles (UAV) due to its potential benefits over conventional configurations in stealth capability, aerodynamic performance, and structural efficiency**.** Compared with the conventional configuration, flying wing aircraft has become the research hotspot of advanced aircraft in recent years [3], and the number of flying wing aircrafts which have been developed successfully is far less than the number of aircrafts with the conventional configuration**.**
Currently, the objective of an aircraft design is to determine an optimum design considering multiple analysis disciplines. The process of aircraft design is a complex process that is composed of many different disciplines. From the early 1960s, it was clear that optimization of a single discipline cannot guarantee the overall optimum design[4]. The concept of multidisciplinary design optimization (MDO) was introduced in the 1980s to manage interdisciplinary connections in design optimization. Since then, MDO has been widely used in different fields of engineering design**.**
Aircraft wing design using Multidisciplinary Design Optimization (MDO) techniques is a complex task

which involves different disciplines, mainly aerodynamic and structure. Different levels of analysis are used for wing design and optimization. Typically simple empirical methods are used in the earliest stages of the concept design. The design task proceeds towards the final design by increasing the complexity of the analysis methods. For instance, a variety of methods are available for aerodynamic analysis of a wing; from a simple lifting line theory or a vortex lattice method up to complex Euler and Reynolds-Average Navier-Stokes methods. Similarly for structural weight estimation, various methods with different levels of fidelity are available. The difficulty lies in the quest or development of analysis methods which are sufficiently simple to be used thousands of times during the optimization. At the same time, these methods should be sophisticated enough to capture changes in the local geometry. Multidisciplinary Design Optimization or MDO, is a methodology for the design of systems in which strong interaction between disciplines motivates designers to simultaneously manipulate variables in several disciplines[5].

Cramer et al [6] suggested , the multidisciplinary feasible (MDF) method is the traditional MDO approach and it involves solving a single optimization problem that calls a multidisciplinary analysis (MDA) when objective or constraint values are required. The MDA solves the governing equations for all disciplines. The MDA module takes the design variables solves all governing equations until the coupling variables have converged. The values of the objective and constraints can then be computed. By requiring the solution of the MDA at each design point, MDF ensures that each optimization iteration is multidisciplinary feasible. This is a very desirable property, since if the optimization is terminated prematurely, a physically realizable design point is at hand. The effort required to implement MDF for a given problem is directly related to the effort required to build an appropriate MDA module.

Antoine and Kroo [7] introduce environmental performance in a MDO framework for preliminary aircraft design and the results obtained had shown that significant environmental impact reduction can be achieved by flying slower and at lower altitudes**.** Noise reduction has also been included in multidisciplinary optimization[8] [9] [10]. Henderson et al. [11] have also reported an aircraft environmental design and optimization framework.

A flying wing UCAV MDO problem was formulated and successfully solved using two different approaches. The first approach was optimization using a low-fidelity design framework. The second approach was variable fidelity optimization with MDO implementation of the GVFM algorithm. Variable fidelity optimization exhibited more design improvement with an acceptable computational cost compared to low-fidelity optimization[12].

The goal of the present study is to optimize the range of a regional jet aircraft using a monolithic MDO technique. The wing of Bombardier CRJ700 aircraft is chosen and its specification shows in Table 1. Alloy Al 7075-T6 was considered as the material used in the manufacturing of the wing. The Breguet range is considered as objective function and to maximize it, both wing structure weight should be minimized and simultaneously maximized the lift to drag ratio of wing. To do this type of optimization, Multidisciplinary Feasible (MDF) method is selected which could couple both structure and aerodynamic equations.

Table 1: Bombardier CRJ700 specifications

specification	*value*
Range	R = 1.685 n.mi
Cruise Mach number	M = 0.78
Cruise altitude	H=3500 ft
Wing span	B=23.24 m
Thickness/chord ratio	t/c=0.12
Max. section lift coefficient	$c_{lmax} = 0.6$
Engine SFC (GE CF34)	SFC=038
Take-of weight	TOW=323608N
Operating empty weight	OEW=193498N

2. Equations

The paper use Breguet range calculate fuel consumption as a function of structural weight and aerodynamic performance that showed in Eq1.

$$R = \frac{V}{SFC}\frac{L}{D} ln\left(\frac{W_{initial}}{W_{final}}\right) \qquad (1)$$

For a wing with sweep $\Lambda = 30^0$, a taper ratio $\lambda = 0.3$, and an aspect ratio AR=8, and the combination of jig twists and spar thicknesses that maximize the range of this wing, while ensuring that the wing structure will not fail at a maneuver condition with a load factor n 2.5**.**

In this investigation, Multidisciplinary Feasible (MDF) is chosen and all results are obtained from this approach. The aim of present work is to modify the wing of Bombardier CRJ700 that is reached to the maximum range. Standard form of the problem can be mathematically stated as,

$$\text{Maximize} \quad R\,,\ \left\{R = \frac{V}{SFC}\frac{L}{D}\ln\left(\frac{W_{initial}}{W_{final}}\right)\right\}$$

With respect to x

Subject to L-W=0

$$n\sigma_j - \sigma_{yield} \le 0$$

Where x is design variable and contains spar thickness (t) and jig twists (γ). L and W are lift force and weight of wing, individually. Load factor is called (n), too.

Problem statement in the form of MDF can be expressed as;

$$\text{Minimize } -R\,,\ \left\{R = \frac{V}{SFC}\frac{L}{D}\ln\left(\frac{W_{initial}}{W_{final}}\right)\right\}$$

$$\text{With respect to} \qquad t,\ \gamma$$

$$\text{Subject to} \qquad n\sigma_j(u) - \sigma_{yield} \le 0$$

$$L(\Gamma) - W(t) = 0$$

Where the aero-structural analysis is as,

$$\text{Aerodynamic governing equation:} \quad A\Gamma = v(u)$$

$$\text{Structural governing equation:} \quad Ku = f(\Gamma)$$

The angle of attack at which the wing flies is returned to the wing to see the resulting lift (= weight of the spar + fixed non-spar weight). In addition, the program will return the lift and elastic twist distributions, and the stress distribution on the spar. The stress distributions can be used to specify material failure constraints. Moreover, the objective function, design variables, and constraints are clearly identified in table 2.

Table 2: classification of objective function, design variables, and constraints

Objective function	$-R = -\frac{V}{SFC}\frac{L}{D}\ln\left(\frac{W_{initial}}{W_{final}}\right)$
Design variable	Spar thickness= t Twist= γ
Constraints	$n\sigma_j(u) - \sigma_{yield} \le 0$ $L(\Gamma) - W(t) = 0$

Furthermore, Fig. 1 illustrates flow chard of the problem with MDF approach and data flow. As shown in the figure, the initial values of design variables are given and then the coupled governing equations of structure and aerodynamic parts is solved. Subsequently, the objective function would be calculated based on the results of MDA. The optimization algorithm will try to find the best output and finally the algorithm will check the answer of optimization process. If the optimized output is matched with the solution of governing equations, the simulation would be stopped otherwise the optimized output will be mentioned a new design variables and run the procedure again.

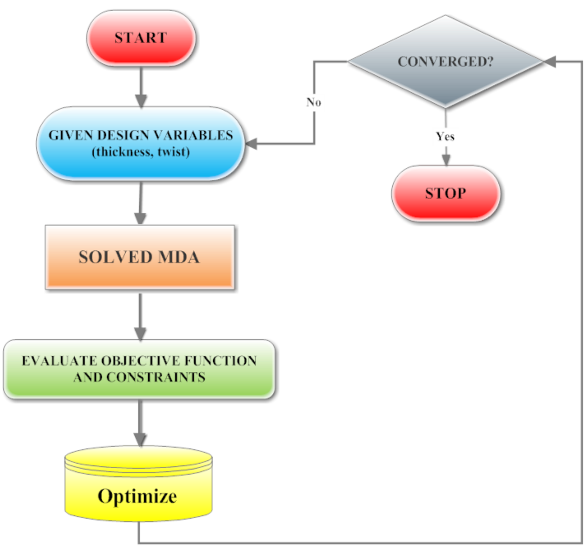

Fig. 1:MDF flowchart

3. Result

This investigation is also solved by using Vortex Lattice Method (VLM) for aerodynamic governing equation and coupled it to structure equation thus the MATLAB function, Fmincon is the final step of converging of this program. Therefore, the maximum range of the mentioned aircraft will be **2378.65** (n.mi).

Moreover, lift, drag forces, and weight of wing, which are obtained in maximum range, are represented in table 3.

Table 3: Loads characteristic at maximum range

Lift	Drag	Weight	Range
2.83×10^5	1.62×10^4	2.83×10^5	2.37865×10^3

According to the MATLAB's results, maximum range increase from 1.685 to 2378065 (n.mi). Furthermore, lift distribution extracted from MATLAB in fig 3 and showed us the optimized wing and base wing's lift distribution.

For an optimum aerodynamic performance of a wing, the desired lift distribution would be elliptic; because this distribution generates the lowest induced drag, ensuring optimum aerodynamic performance of the wing. As shown in the figure3 , it matter how oval the lift diagram is, means we have better lift force.

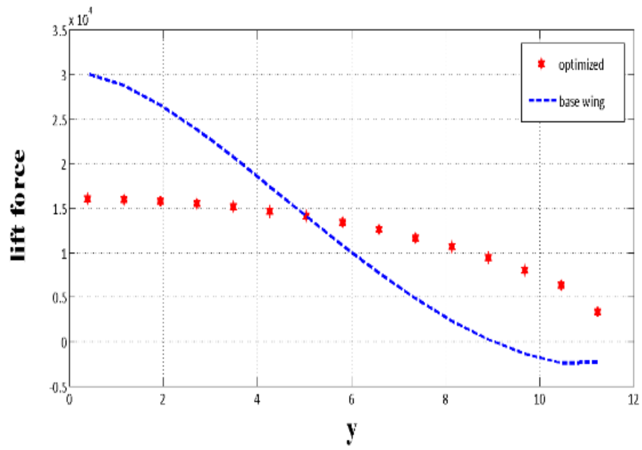

Fig. 3: Lift distribution according to wing span

In this research, aerodynamic is not just considered; structure of wing should be regarded, too. Therefore, the lift distribution will not be an elliptic.

Actually, wing weight reduction and stress play an important role in this problem. Stress is high in the wing root and thicker spar is sufficient. Therefore, weight of wing in the root rises. On the other hand, any increase in drag would bring a large penalty in weight especially in a long-range aircraft. Therefore, lift curve shifts towards and it becomes triangular and induced drag is declined.

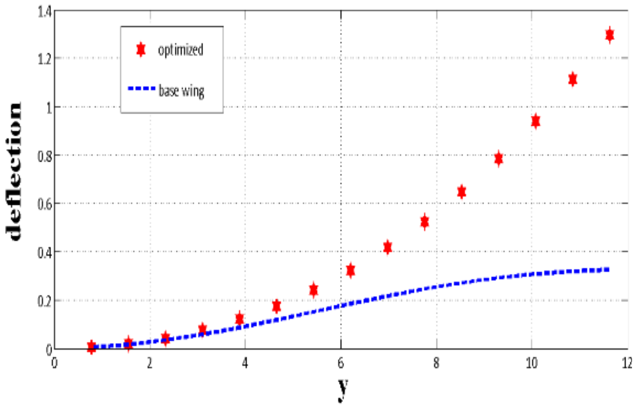

Fig. 4.: deflection distribution across wing span

According to the figure 4 the investigation has higher deflection after optimizing. the tip of the wing (the end of the wing) is so light because of this the wing has so much deflection.

Conclusion

this paper optimize the **Bombardier CRJ700** aircraft by multidisciplinary design optimization to achieve the best range.

With supplying Breguet range and coupling aerodynamic and structural governing equation MDA and MDF the Branch of MDO completed and finally lead the results to maximum range of the flight and optimum aerodynamic performance of a wing such lift and the desired lift distribution would be elliptic lift. Hence it leads to optimum deflection on structural performance. wing weight reduction and stress play an important role in this problem thus after optimize weight of wing in the root increases.

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