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Performance based MDO of a morphing Joined-Wing aircraft concept

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Abstract

The aeronautic industry is currently facing requirements of contradictory nature: the demand for speed and capacity increase; and the need to minimize the environmental impact caused by air travel. In order to enhance global performance and efficiency of aircraft, novel configurations and morphing solutions have been proposed. To achieve either an optimal configuration or an optimal morphing strategy for a determined mission, it is necessary to explore Multidisciplinary Design Optimization (MDO) solutions in the conceptual design phase.

A MDO framework has been developed for preliminary design and analysis of novel configurations, including the capability to analyze morphing solutions. This design optimization tool was implemented to be both modular and versatile, allowing the user to create custom plug-in like modules to tailor the software to each user's needs. In this framework, the principal aircraft disciplines are integrated with optimization software in a single optimization statement. With computational efficiency in mind, surrogate models of the disciplines are built and the quality of these approximation models is verified. Disciplines can be replaced by corresponding existing or pre-calculated databases.

In this paper, a conceptual joined-wing aircraft with a morphing wingtip able to bend and twist is optimized with the goal of increasing roll and yaw authorities in order to evaluate the possibility of introducing this type of morphing device to enhance lateral-directional control. This concept aircraft is one of the planforms employed within the scope of the project "Novel Aircraft Configurations: from Fluttering Wings to Morphing Flight (NOVEMOR)" under the EU 7th framework program.

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1. INTRODUCTION

The aeronautic industry is currently facing several challenges of contradictory nature. On one hand there is the need to increase speed and capacity due to predicted air travelling growth, which according to recent studies will increase at an average annual growth between 3 to 5%[1]. On the other hand the introduction of severe regulations[2] in air transport namely regarding noise and emissions reduction have impelled the design of "greener" aircraft that aim to reduce the environmental impact caused by them. Summarizing, the main goal in aircraft design is to achieve an aircraft such that it is the most efficient possible during flight, while at the same time it respects the imposed environmental requirements.

It is necessary to explore Multidisciplinary Design Optimization (MDO) solutions in the conceptual design phase to tackle the contradictory nature of the requirements. Several works has been done in the area of performance based MDO. Antoine and Kroo[3] introduced environmental performance in a MDO framework for preliminary aircraft design. Henderson et al[4] developed an aircraft environmental design and optimization framework. Recently Liem et al[5] optimized a flight mission profile with DOC (Direct Operative Costs) minimization as design goal.

This work was developed in the scope of the EU 7th Framework Project NOVEMOR. The aim of the **NOVEMOR** (**NO**vel **A**ir **V**Ehicle Configurations: From Fluttering Wings to **MOR**phing Flight) research project is to investigate novel air vehicle configurations with new lifting concepts and morphing wing solutions to enable cost-effective air transportation.

One of the discussed novel configurations inside NOVEMOR project was the joined-wing configuration. The Joined-Wing (JW) aircraft is an unusual configuration, which is characterized by its diamond shape when seen from the top and front views. This configuration is composed of two lifting surfaces (main and aft wings) connected at a joint point. The aft wing replaces the horizontal tail for stability and trimming while contributing significantly to the total lift of the aircraft. The JW is in fact an old concept, for instance since aviation first steps configurations having tandem wings connected have been proposed[6], but the design as it is recognized today was developed by Dr. Julian Wolkovitch in the 1980's[7]with the promise of reducing structural weight and stiffness while at the same time reducing drag. According to Torenbeek[8] the joined-wing design has several inherent benefits over the fixed-wing configuration and should be handled as a serious candidate to improve flight efficiency for widely different capacity airliners. Since this configuration was proposed several studies were conducted to assess the possible advantages and disadvantages. In Table 1 are given some of the claimed advantages and disadvantages of this unconventional design.

Table 1. Claimed advantages and disadvantages of the joined-wing design.

Pros	Cons
• Lighter structure	• Aft wing buckling
• Higher stiffness	• Design integration
• Higher flutter speed	• Propulsion integration
• Higher aileron effectiveness	• Reduced chord extension to install high lift devices
• Low vortex drag	• Costly to manufacture and maintain
• Low wave drag	• Pitch-down tendency

Taking into account that the joined-wing is still a concept not yet implemented at the industry level, a conceptual reference joined-wing aircraft is used in the NOVEMOR project[9] and it is shown in Figure 1.

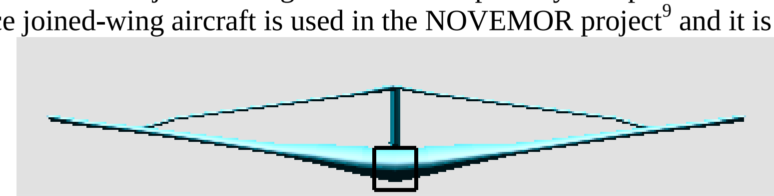


Figure 1. NOVEMOR project Reference Joined-Wing Aircraft.

This conceptual design presents poor lateral directional stability. So in order to improve the stability of the design, the joined-wing wingtip was enabled with a morphing device such that the wingtip is able to bend and twist. The benefits of having a morphing wingtip are compared with the application of conventional control surfaces to the design.

2. MDO FRAMEWORK

A MDO architecture was implemented in the framework of the NOVEMOR project of the EU 7th Framework Program, in order to enhance flight performance through investigating morphing solutions and novel configurations and to perform several different types of MDO problems (Figure 2). This tool includes the principal aircraft disciplines, such as: aerodynamics (panel method); structures (equivalent beam model); propulsion (ideal turbofan or turboprop engine model); geometry; weights distributions; performance; stability; and control.

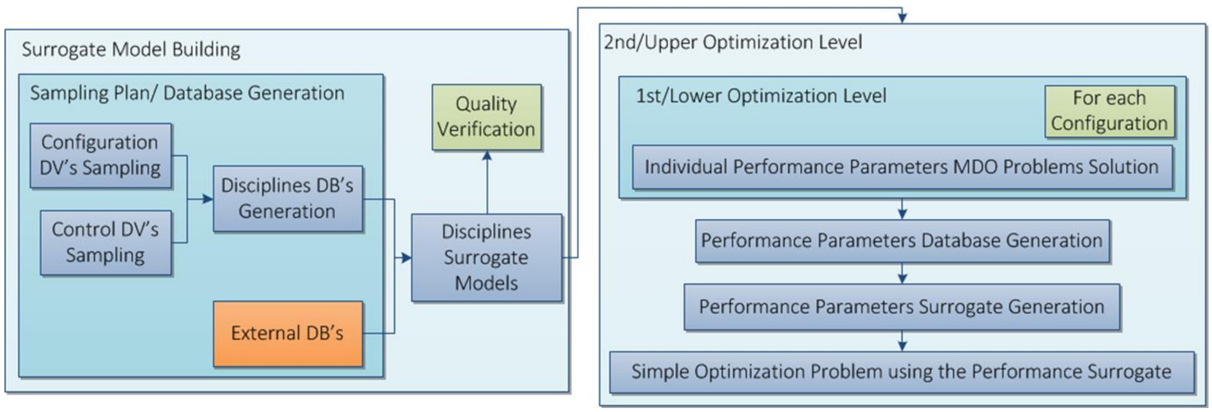


Figure 2. Implemented MDO architecture.

The designed architecture was divided in two level of optimization. In the first/lower level, multi-MDO problems with performance targets are solved, and any parameter that is able to change during flight can be employed as design variables. In the second/upper optimization level a single MDO problem is defined based on the selected performance goals of the first level, which can be included in weight sum objective function and/or set as constraints to the problem.

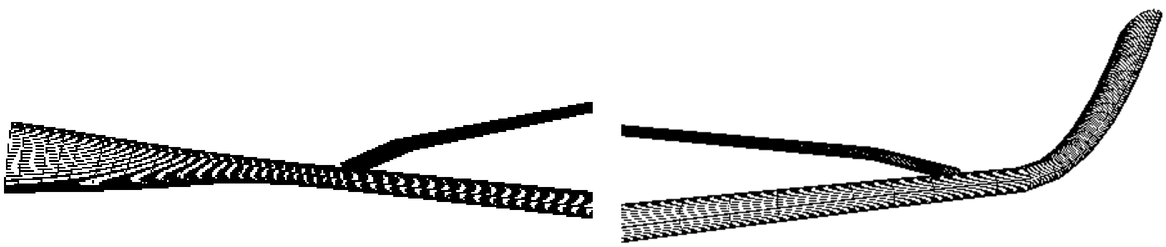
With computational time reduction in mind, surrogate models are employed to reduce the optimization process time. Approximation models are used to replace the disciplines in the lower level of optimization, which are generated after performing a sampling of these disciplines. The sampling process can be replaced by externally generated databases that can be a result of higher fidelity models runs or experimental data. A surrogate model of the performance goals is as well generated; this way reduce the accuracy of the results, but allows to exclude configurations and select the most promising solutions in a considerable shorter time. The possibility of using the real models instead is also available, nonetheless for the present computations the surrogate models were applied.

The entire optimization process is conducted in the optimization module. Two different optimization algorithms are included in this framework, a Feasible Sequential Quadratic Programming[10] (FSQP) optimizer and an in-house genetic algorithm code. All the optimizations done in this work were performed using the FSQP optimizer.

For this paper, the MDO tool is applied to a conceptual joined-wing aircraft with the purpose of improving lateral stability, while maintaining maximum stress criteria, trimming conditions and sufficient roll authority. In this application case the wing internal structure and also the aircraft controls (bending and twist actuations of the wingtip) are optimized.

3. MAXIMIZATION OF ROLL AND YAW AUTHORITY

Firstly, a study to evaluate the yaw and roll authorities of the reference model was performed. The benefits of having a wingtip able to change during flight were assessed to improve yaw and roll authorities at low speed (30 m/s) and altitude (sea level) when compared with conventional control surfaces. For this test case only control variables were employed in the optimization process and therefore just the 1st level of optimization of the MDO architecture is applied. Bending and twist morphing controls at the wingtip were selected to be the design variables set for this optimization problem (Figure 3). Only aerodynamics were considered and no multidisciplinarity was added to this test case.



(a) - Twist Morphing Control **(b)** - Bending Morphing Control

Figure 3. Morphing/Control Variables.

Two different optimization problems were defined. In the first problem, the roll moment coefficient (C_l) is maximized using the bending and twist morphing control. The benefits of having a morphing wingtip are evaluated by comparing the results with the ones attained by optimizing conventional ailerons controls placed on the outboard wing of the joined-wing aircraft. In the second problem, the yaw moment coefficient (C_n) for a fixed side-slip angle (β=5º) is maximized using the same morphing controls and the benefits are evaluated in comparison with the clean joined-wing configuration since no conventional control such as a rudder exist in this concept model.

In order to prevent numerical instabilities in the optimizer, two different configurations of the bending morphing control were used: symmetric and anti-symmetric configurations. In the symmetric configuration both right and left wingtips bend up, while in the anti-symmetric configuration the left wingtip bends up and the right wingtip bends down.

The complete set of design variables used in the devised optimization problems are presented in Table 2.

Table 2. Design Variables Boundaries for the Joined-Wing Optimization Problems

Design Variables	Lower Boundary	Upper Boundary
Right Tip Height [m]	0.011	0.700
Left Tip Height [m]	0.011 (Symmetric) -0.700 (Anti-Symmetric)	0.700 (Symmetric) -0.011 (Anti-Symmetric)
Right Twist [º]	-10	10
Left Twist [º]	-10	10
Right Aileron [º]	-35	25
Left Aileron [º]	-35	25
Angle of Attack [º]	-10	10

3.1 Maximize Roll Moment Coefficient

The reference model has conventional ailerons that can mechanically deflect 25 degrees up and 35 degrees down. Aiming to evaluate the benefits of employing morphing controls in this aircraft, two optimization problems were formulated with the objective of maximizing the roll moment coefficient, C_l. Only one constraint was imposed, which was level flight condition. The first optimization problem determines the ailerons deflections which perform the highest roll moment; while in the second it is determined the optimal morphing wingtip parameters (bending and twist) that maximize the roll moment coefficient for the symmetric and anti-symmetric configurations. Besides the ailerons deflection, the bending and the twist parameters, the angle of attack was set as a design variable to ensure a level flight.

Table 3. Roll Moment Coefficient Maximization Results.

Configuration	Angle of Attack [º]	Right Tip Height [m]	Left Tip Height [m]	Right Twist [º]	Left Twist [º]	C_l [-]	C_n [-]	T [s]
Clean with Ailerons	2.74	-	-	-35.00	25.00	0.0462	0.0018	0.47
Twist Only	2.60	-	-	-10.00	10.00	0.0150	0.0002	0.83
Symmetric	2.74	0.0516	0.0119	-10.00	10.00	0.0088	0.0005	1.08
Anti-Symmetric	2.74	-0.0145	0.0210	-10.00	10.00	0.0085	0.0001	1.10

From Table 3 it is observable that the clean configuration with conventional control surfaces provides a higher roll moment coefficient than the other configurations (the Right Twist and Left Twist correspond to Right Aileron and Left Aileron deflections respectively, for the clean configuration). It is interesting to see that the twist evolves in the same manner of the aileron deflection, although not achieving the same amount of roll moment.

Assuming a constant acceleration, these values of roll moment coefficient would cause a change in bank of 60º in 0.83s, 1.08s and 1.10s for the twist only, symmetric and anti-symmetric configurations respectively, which compared with the 0.47s of the clean configuration shows a considerable decrease of roll authority.

The symmetric and anti-symmetric configurations that achieved the highest roll authority are shown in Figure 4.

(a) - Symmetric Configuration **(b)** - Anti-Symmetric Configuration

Figure 4. Joined-Wing Configuration for Roll Moment Coefficient Maximization.

3.2 Maximize Yaw Moment Coefficient

Due to the absence of a rudder in this concept aircraft the comparisons with the morphing wingtip for the yaw authority maximization problem are in regard to the clean configuration. Two optimization problems were defined and just like in the previous study, a level flight constraint was considered. The first optimization problem only levels the aircraft flight with the angle of attack, while in the second problem the morphing wingtip parameters (bending and twist) are determined to maximize the yaw moment coefficient, C_n. Besides the ailerons deflection, the bending and the twist parameters, the angle of attack is used to ensure a level flight for both problems.

Table 4. Yaw Moment Coefficient Maximization Results.

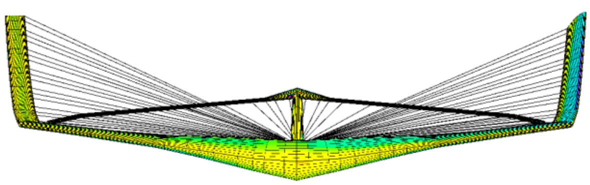
Configuration	Angle of Attack [º]	Right Tip Height [m]	Left Tip Height [m]	Right Twist [º]	Left Twist [º]	C_n [-]	C_l [-]	T [s]
Clean	2.74	-	-	-	-	0.0029	-0.0033	1.88
Symmetric 1	2.76	0.7	0.7	-10	10	0.0216	-0.0144	0.69
Anti-Symmetric 1	2.39	0.7	-0.7	10	10	0.0212	-0.0042	0.70
Symmetric 2	2.67	0.5	0.5	-10	10	0.0151	-0.0152	0.82
Anti-Symmetric 2	2.29	0.5	-0.5	10	10	0.0155	-0.0051	0.81

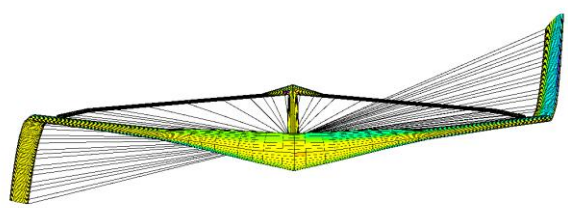
Since the aircraft does not have a rudder it was expected that the yaw moment coefficient would be much higher for the morphed aircraft than for the clean joined-wing configuration, which the results confirmed: (as one can observe from Table 4) comparing the two morphed configurations, the symmetric configuration achieved a higher C_n than the anti-symmetric configuration (1.9% more), although with a much lower roll moment coefficient.

Assuming a constant acceleration, these values of yaw moment coefficient would cause a change in heading of 60º in 0.69s and 0.70s for the symmetric and anti-symmetric configurations respectively, which compared with the 1.88s of the clean configuration shows a considerable increase of yaw authority.

For more conservative tip heights values, the yaw authority decreases, reducing the time response for a change in heading of 60º, assuming a constant acceleration, but still having higher yaw authority than the clean configuration. Associated to this decrease in roll moment coefficient, there is a small increase of yaw moment coefficient.

In Figure 5, the symmetric and anti-symmetric configurations that achieved the highest yaw authority are shown.





(a) - Symmetric Configuration **(b) -** Anti-Symmetric Configuration

Figure 5. Joined-Wing Configuration for Yaw Moment Coefficient Maximization.

5. CONCLUSIONS

A morphing wingtip concept able to bend and twist was applied to a joined-wing concept aircraft, with different performance results in the first study. From one side a considerable increase in yaw authority was achieved for low speed and altitude for an anti-symmetric joined-wing configuration in comparison with a clean configuration of the aircraft, which does not have rudder. However a decrease in roll authority was found as well by replacing the ailerons with the morphing wingtip, for the same low speed and altitude.

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project aimed at developing, implementing and assessing a range of numerical simulation technologies to accelerate future aircraft design. Advances in morphing technologies will lead to more efficient and greener aerostructures. The partners in NOVEMOR are: IST Lisbon, Politecnico di Milano, University of Bristol, KTH, DLR, CSIR and Embraer.

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