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Performance based multidisciplinary design optimization of morphing aircraft

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A B S T R A C T

The aeronautical industry is currently facing contradictory aircraft design requirements. There is a need to increase speed and capacity while minimizing the environmental impact. Novel configurations and morphing solutions are being proposed to address these requirements. In order to achieve the optimal aircraft configuration or the best morphing solution for a given mission, it is necessary to explore Multidisciplinary Design Optimization (MDO) solutions during the conceptual design phase. To this end, a MDO framework is proposed for conceptual design and analysis of new aircraft configurations, including the capability to analyze and quantify the effect of morphing wing solutions on aircraft performance. To illustrate the versatility and capabilities of the MDO tool, the design of a morphing wingtip on a conventional aircraft for two different flight conditions is assessed based on a reference model transport aircraft. Also, the performance of a morphing bending and twist control applied to a reference joined-wing configuration to improve lateral-directional stability is quantified. The results obtained show a significant reduction in fuel consumption when introducing a wingtip, although an incremental and negligible reduction was verified when enabling the wingtip with morphing capabilities. A considerable increase in yaw authority was achieved for the joined-wing model with the bending-twist morphing wingtip, however this morphing concept was not able to reach the same roll authority as conventional ailerons.

1. Introduction

Currently the number of people who can afford to travel is increasing each year and the current forecasts predict a continuous growth of both passenger and freight traffic at an average rate of 3 to 5% per year, with freight being expected to increase slightly more, both significantly above global GDP growth [1]. Consequently, 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 example, the requirements stated in the Flightpath 2050 vision for European aviation [2] 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 [3].

Due to the contradictory nature of the goals of environmental impact reduction and increase 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. With global performance in mind, the better part of the knowledge, gathered over the past few years, in aerodynamics and structures, associated with the permanent need to improve aircraft in both performance and efficiency, have impelled not only the use of new aircraft configurations, but also the introduction of morphing solutions in the existing configurations.

Looking at actual transport aircraft it is very easy to identify many similarities in shape and configurations of different airplanes, even if during the last decades great technological improvements have been reached, for example concerning engine emissions and noise reduction, high-lift device configurations and advanced materials. One of the reasons is related to the fact that configuration and performance of commercial aircraft, especially fixed-wing aircraft, have been optimized within a limited range of conditions, especially cruise conditions, in terms of speed and

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altitude. Outside this range, aircraft behavior is less than optimal [4,5].

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 multi-functionality 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. These integrated systems possess a functionality that adds significant value to materials, technologies or end-products, which in turn enables system performance enhancements that are not possible with traditional conventional approaches.

Many modern aircraft present fixed wingtips/winglets nowadays. Only recently these devices were implemented in civil transportation, due to the fact that new wingtip configurations were introduced where the induced drag reduction offsets the extra cost and weight, producing a net benefit [6].

The current wingtips/winglets are rigid and were optimized with requirements of different flight conditions/missions, which in some cases can be contradictory. Furthermore, the wingtip/winglet designs have to fulfill the geometric constraints imposed by airport terminals and maintenance facilities. Morphing devices can surpass these limitations by enabling the wingtips/winglets to adopt the optimal configuration for each fight condition, improving the aircraft global performance (in terms of parameters such as speed, maneuverability, runaway requirements, climb performance, range, endurance and fuel consumption) and/or extending its fight envelope [6].

In the future, it can be possible to use morphing wingtips/winglets for specific tasks, like reducing the wake turbulence of the aircraft, improving the aeroelastic behavior (*e.g.* to suppress flutter or alleviate gust loading) or even controlling shock wave formation and/or propagation [6]. Moreover, the morphing wingtips/winglets modify the aerodynamic forces and moments on the wing as well as its gravity center [6]. This can be applied to increase or completely replace traditional control surfaces [7].

Several studies have been carried out using morphing wingtip/winglet to improve flight performance and/or to enhance aircraft maneuverability. Different wingtip/winglet concepts have been proposed with different control parameters including its span and the angles of toe (twist), cant (dihedral) and sweep.

Bourdin et al. [8] and Gatto et al. [9] proposed a morphing wingtip able to change the cant angle to improve aircraft control and replace conventional control surfaces. However, to achieve trim conditions they required elevator. A split morphing wingtip that can be controlled independently was proposed by the same authors [10,11]; the concept presented an efficiency improvement for low-speed flight with moderate to high lift coefficients.

A morphing winglet concept, named MORPHLET, was proposed by the Morphing Wings research group at the University of Bristol [12]. This morphing winglet concept able to change cant and toe (twist) angles and span was developed to enhance flight efficiency for a given flight envelope. MDO was applied to improve the Specific Air Range (SAR) and a potential gain between 4 and 5% was verified for all the investigated flight phases (start of initial range, start of final cruise and end of descent) [13].

A morphing wingtip concept mechanism was proposed by Falcão [6,14] servo-actuated with the ability to change toe, cant and sweep angles. Several optimization problems were devised to increase wing efficiency in different flight performance goals, including range, endurance and stall speed.

This work is being developed in the framework of the EU 7th Framework Project NOVEMOR [15]. The aim of the NOVEMOR (NOvel Air VEhicle Configurations: From Fluttering Wings to MORphing Flight) research project is to investigate novel air vehicle configurations with new lifting concepts and morphing wing solutions to enable cost-effective air transportation. The design and development of the proposed solutions have been performed as an integral part of the aircraft conceptual design, rather than just as an add-on later in the design cycle, thus enabling innovative aircraft designs to be made through the use of morphing structures technologies. Such concepts will enable improved aircraft efficiencies, aerodynamic performance, reduced structural loads and lighter weight structures, leading to overall lower fuel consumption and therefore improvement on the greening level of the aircraft.

Recently, related works have been reported in the literature in the area of aircraft performance optimization taking into account environmental requirements. Antoine and Kroo [16] 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 [17,18,37]. Henderson et al. [19] have also reported an aircraft environmental design and optimization framework.

A MDO framework that includes all aircraft disciplines such as aerodynamics, structures, propulsion, stability and control has been developed. In this tool, the environmental requirements of emissions and noise can also be included in the design process as well as an estimation for the direct operation costs, although in this work, only the fuel consumption reduction is taken into account as a mean for reducing emissions and direct operation costs. This tool computes surrogate models of the disciplines using databases, and these databases can be replaced by higher fidelity computational databases, if needed. The employment of surrogate models allows to significantly decrease the optimization time [20]. In the developed framework these models are generated using Kriging method, although there is also the capability of using polynomial regressions or radial basis functions. Kriging is a method formally developed by Matheron [21] based on the work by Krige, which was more recently applied to modeling [22] and optimization [23] problems. The code used in the developed framework was based on the DACE software tool [24]. The main aim of this tool is performance based optimization of an aircraft, which includes morphing capabilities. Two levels of optimization are conducted in the framework. The first optimization level consists in improving the aircraft performance of a fixed configuration optimizing the controls, which in the case of morphing means calculating the morphing strategies. The second level aims to optimize the aircraft configuration for the best performance based objective function.

For this work, a special module was built to perform automatically several comparisons between wingtip shapes for two flight conditions (cruise and climb). Summarizing, the prime goal of this script is to assess the benefits of including a morphing wingtip in a conventional regional jet aircraft and in a conceptual joined-wing (JW) aircraft.

2. MDO framework

The developed framework was implemented with a unified aircraft multidisciplinary optimization environment in mind. From the early development stages, the software was designed to be versatile and modular, and with a well-defined graphical user interface, focused on being user friendly and comprehensive. The