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Optimization and design of a morphing wing tip aircraft demonstrator for drag reduction at low speed, Part I – Aerodynamic optimizations using genetic, bee colony and gradient descent algorithms

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Abstract In this paper, an 'in-house' genetic algorithm is described and applied to an optimization problem for improving the aerodynamic performances of an aircraft wing tip through upper surface morphing. The algorithm's performances were studied from the convergence point of view, in accordance with design conditions. The algorithm was compared to two other optimization methods, namely the artificial bee colony and a gradient method, for two optimization objectives, and the results of the optimizations with each of the three methods were plotted on response surfaces obtained with the Monte Carlo method, to show that they were situated in the global optimum region. The optimization results for 16 wind tunnel test cases and 2 objective functions were presented. The 16 cases used for the optimizations were included in the experimental test plan for the morphing wing-tip demonstrator, and the results obtained using the displacements given by the optimizations were evaluated.

1. Introduction

In the context of a world in continuous change, the aerospace industry must develop greener and more efficient airplanes that will consume less fuel and have a lower CO_2 footprint. Therefore, new methods must be developed for improving the flight behavior of airplanes through the optimization of their existing properties.

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Many optimization methods have been developed and could be used in the aerospace research. Xiang and Gao[1] provided an exhaustive presentation of various optimization algorithms inspired from the natural world's behavior,[2] physical[3] and chemical[4] properties, and also algorithms based only on abstract mathematical theory.[5]

Applications of optimization algorithms can now be found in almost all industrial and academic research venues, from electric circuitry[6] to stock market predictions,[7] image quality problems[8] and software implementation problems.[9]

In aerospace, many research projects and collaborations include the successful implementation of the more traditional metaheuristic optimization algorithms such as genetic algorithms, bee colony algorithms, artificial neural networks or ant colony optimization in their research for new optimized flight trajectories, wing shapes and control techniques. One such collaboration took place between the teams of the LARCASE Laboratory and CMC Electronics-Esterline for their project, which was funded by the Green Aviation Research Development Business Led Network (GARDN) in its second round.[10,11] The main objective of the collaboration was to optimize the vertical and horizontal paths of an aircraft within the flight management system by taking into account the required time of arrival, the wind grids and meteorological conditions. The main motivation of the project was to reduce overall carbon emissions and costs associated to aircraft flight.

Applications of optimization techniques for small aircraft were described by Gamboa et al.[12] in their design of an unmanned aerial vehicle (UAV) morphing wing capable of independent span and chord changes, using a telescopic spar and a rib system. The numerical analysis demonstrated a drag reduction of up to 23% when compared to the non-morphing geometry. Falcão et al.[13] designed and tested a morphing winglet for a military UAV, achieving important performance improvements by simply changing the winglet cant and toe angles. Other research on UAV wing morphing was done by Sugar et al.,[14,15] where the upper surface of the wing was optimized on a segment between the leading edge and 55% of the chord, and in which the morphing of the full wing's geometry was also explored; and by Hu and Yu[16] who studied a multidisciplinary optimization for improving aerodynamic, stealth and structural performances of an unmanned aerial combat vehicle. Li et al.[17] developed a methodology for aerodynamic optimization aimed at demonstrating the performances of a blended wing body transport, while Xie et al.[18] studied the effects of static aeroelastic phenomena on very flexible wings.

Other experiments were conducted in the area of 'active airfoil optimization'. One of these experiments was performed in the CRIAQ 7.1 project, in which collaboration took place between aerospace industrial teams at Bombardier Aerospace and Thales Canada, academic partners from the École de Téchnologie Supérieure (ETS) and École Polytéchnique of Montreal, and researchers at the Canadian National Research Council (CNRC). The purpose of this project was to demonstrate the capabilities of morphing wings in a wind tunnel for developing the flow transition from laminar to turbulent.[19,20] Morphing was achieved by replacing the upper surface of the wing, spanned between 7% and 70% of the wing chord, with a flexible carbon-Kevlar composite skin. The skin morphing was achieved using two shape memory alloy (SMA) actuation lines to obtain an optimized shape for each flight condition tested in the wind tunnel.[21] The optimization was done using a genetic algorithm method coupled with the aerodynamic solver XFoil. The wind tunnel tests had proven that the concept of upper surface morphing was viable, controllable, and provided tangible results confirming the delay of the transition from laminar to turbulent flow, thereby inducing a substantial reduction in the drag coefficient.[22] PID[23] and neuro-fuzzy controllers[24] were tested to prove the ability of the flexible upper surface and the morphing mechanisms towards the transition delay. The controllers demonstrated an excellent performance in both open[25] and closed loops.[26]

Exhaustive state of the art listings of wing geometry optimization research are presented by Sofla et al.[27] and Vasista et al.[28]

The research presented in this paper concentrates on the practical application of an 'in-house' developed genetic algorithm to determine the optimum shape of the wing upper-surface that leads to improvements in the flow behavior on the upper-surface of the wing. The paper focuses on the design aspects of the optimization algorithm, depending on the imposed constraints, and on the practical aspects of a multidisciplinary optimization applied to the aerodynamic improvement of an airfoil shape. The optimization concentrated on the improvement of the upper-surface behavior of the flow by changing the position of the transition from fully laminar to fully turbulent flow. The optimization was carried out at the airfoil level and, in practice, was applied to a full-scale wing tip with an aircraft-type internal structure. Comparisons were performed between the results obtained with this 'in-house' genetic algorithm and two other methods: bee colony (BC) algorithm and gradient descent (GD). These comparisons led to the conclusion that the 'in-house' algorithm could be used for the experimental validation using wind tunnel testing for all test cases.

2. Presentation of research context

The research presented in this present paper was done within the framework of the international CRIAQ MDO505 Morphing Wing project. The participants in this project were teams from ETS, Ecole Polytehnique of Montreal and University of Naples 'Federico II' as academia research partners, the CNRC and the Italian Aerospace Research Center (CIRA) as research center partners, and Bombardier Aerospace, Thales Canada and Alenia Aermacchi as industrial partners.

The objectives of the project were to design, manufacture and control a wing demonstrator based on an aircraft wing tip equipped with both a conventional and an adaptive aileron. The novelty of the CRIAQ MDO 505 project was the multidisciplinary approach of the project, in which structure, aerodynamics, control and experimental design were combined to design and manufacture an active morphing wing demonstrator and then to test it under subsonic wind tunnel conditions.

Fig. 1 presents the layout and the position of the morphing upper skin on a typical aircraft wing, while Fig. 2 presents the structural elements of the morphing wing model.

The CRIAQ MDO 505 project was a continuation of the former research project CRIAQ 7.1, and aimed at a higher level of technical readiness by considering a real aircraft wing internal structure, a certifiable electric control system and controllers. The objectives of the active morphing wing tip project were mainly: (A) the design and manufacturing of a morphing

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