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A new non-linear vortex lattice method: Applications to wing aerodynamic optimizations

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Abstract This paper presents a new non-linear formulation of the classical Vortex Lattice Method (VLM) approach for calculating the aerodynamic properties of lifting surfaces. The method accounts for the effects of viscosity, and due to its low computational cost, it represents a very good tool to perform rapid and accurate wing design and optimization procedures. The mathematical model is constructed by using two-dimensional viscous analyses of the wing span-wise sections, according to strip theory, and then coupling the strip viscous forces with the forces generated by the vortex rings distributed on the wing camber surface, calculated with a fully three-dimensional vortex lifting law. The numerical results obtained with the proposed method are validated with experimental data and show good agreement in predicting both the lift and pitching moment, as well as in predicting the wing drag. The method is applied to modifying the wing of an Unmanned Aerial System to increase its aerodynamic efficiency and to calculate the drag reductions obtained by an upper surface morphing technique for an adaptable regional aircraft wing.

1. Introduction

The air transportation industry is a commercial and economical sector with a very fast growth rate. The International Civil Aviation Organization (ICAO) estimates that the number of flights will triple by 2040.[1] This growth rate, together with growing global concern for environmental protection and the reduction of greenhouse gas emissions obliges the aerospace industry to search for solutions to improve aircraft efficiency.

One possibility for achieving this desired efficiency is wing morphing, through its active and controlled modification of one or several wing geometrical characteristics during flight. Researchers have proposed different technological solutions for obtaining the desired wing adaptability, with some concepts achieving significant performance improvements with respect to the baseline design. Sofla et al.[2], Stanewsky[3] or Barbarino et al.[4] presented exhaustive reviews on the research performed on various morphing wing technologies, both by academia and by the aerospace industry. Morphing wings were

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used to adapt the wing span and airfoil camber,[5,6] the winglet cant and toe angles,[7] to replace conventional high-lift devices,[8–10] or the conventional control surfaces.[11]

In Canada, the CRIAQ 7.1 project, a collaboration between Ecole de Technologie Superieure, Ecole Polytechnique de Montreal, Bombardier Aeronautique, Thales Canada and the Institute for Aerospace Research – Canada National Research Council took place between 2006 and 2009. The objective of this project was to improve and control the flow laminarity over a morphing wing wind tunnel model, in order to obtain significant drag reductions.[12] The wing was equipped with a flexible composite material upper surface whose shape could be changed using internally-placed Shape Memory Alloy (SMA) actuators.[13] The numerical study revealed very promising results: the morphing system was able to delay the transition location downstream by up to 30% of the chord and reduce the airfoil drag by up to 22%.[14] The actuator optimal displacements for each flight condition were provided by using both a direct open loop approach[15,16] and a closed loop configuration based on real time pressure readings from the wing upper surface.[17,18] In addition, a new controller based on an optimal combination of the bi-positional and PI laws was developed.[19,20] The wind tunnel tests were performed in the 2 m by 3 m atmospheric closed circuit subsonic wind tunnel at IAR-CNRC, and validated the numerical wing optimisations[21] and designed control techniques.[22]

Recently, research on the capabilities of morphing wings equipped with flexible upper surfaces included the optimization of the ATR42 regional aircraft airfoil[23] and of the Hydra Technologies S4 Unmanned Aerial System (UAS) airfoil.[24] Both cases obtained notable transition delays of up to 20% of the chord and significant drag reductions of up to 15%. The morphing system designed for improving and controlling the laminarity of the flow could also provide performance improvements at high angles of attack. For the UAS-S4 airfoil, a 2° increase of the stall angle, with a corresponding increase of the maximum lift coefficient by 6% have been obtained, using the morphing upper skin to delay the boundary layer separation.[25]

In order to obtain three-dimensional wing performance improvements with upper surface morphing, a fast and efficient aerodynamic solver was required. A three-dimensional, non-linear numerical extension of the classic lifting line theory, coupled with a two-dimensional viscous flow solver, gave sufficiently accurate estimations of the aerodynamic characteristics of the UAS-S4 wing.[26] A study of the UAS-S4 wing revealed that for typical cruise and surveillance flight conditions, the morphing wing could provide drag reductions of up to 5%.[27] Further research was performed to determine the influence of the number of internally-placed actuators and their positions along the wing span on the aerodynamic gains. The aerodynamic calculations were done using the numerical non-linear lifting line code, while the optimized upper skin shapes were determined by a novel technique based on a hybrid Artificial Bee Colony (ABC) and the Broyden-Fletcher-Goldfarb-Shanno (BFGS) algorithm.[28]

The CRIAQ MDO 505 project is a continuation of the CRIAQ 7.1 project and is centered on the implementation of the adaptive upper surface morphing concept on a real regional aircraft wing tip. The wing box, including all the spars, ribs and stringers present on the wing, was manufactured from aluminum, while its flexible upper surface, localized between 20% and 65% of the wing chord, was specifically designed and optimized from carbon composite materials. Four in-house manufactured electrical actuators were fixed to the ribs and to the flexible upper skin, inside the wing box. The actuators are located on two parallel ribs, at 37% and 75% of the model span, while on each of the two ribs the actuators are placed at 32% and 48% of the local wing chord.

Unlike the UAS-S4 wing that has a high aspect ratio of 7.61, the MDO 505 wing tip model has a low aspect ratio of 2.32. The lifting line model can be corrected for low aspect ratio wings by using semi-empirical correction factors[29], but a lifting surface model such as the Vortex Lattice Method (VLM) could provide the results without requiring further corrections. In addition, the surface modeling of both span-wise and chord-wise aerodynamic force distributions provides better and more detailed results, even for higher aspect ratio wings, as that of the UAS-S4.

The VLM represents a powerful tool for preliminary wing design and optimization. Initially, the method used a distribution of horseshoe vortices over the wing surface, with only one segment bound to the surface,[30] but researchers presented alternative, more accurate formulations using ring vortices.[31] The unsteady VLM was extensively used to calculate the aerodynamic loads for aeroelasticity and flight dynamics simulations.[32] Recently, the steady VLM was used for multi-objective optimization studies for the existing commercial aircraft,[33] for the development of morphing wings,[34] for Unmanned Aerial Vehicles aerodynamic performance optimizations[35] and for the design of non-conventional Blended Wing Body aircraft geometries.[36]

The theory and the mathematical model behind the nonlinear VLM are detailed in Section 2. Then, in order to test the validity of the method, multiple test cases are performed. Section 3 begins with a grid convergence study to establish the surface mesh requirements. The linear implementation of the VLM code is verified using two reference cases. Validation tests for the new nonlinear VLM formulation are performed considering three wings of different planform shapes. Numerical results expressed in terms of lift, drag and pitching moment coefficient obtained with our code and with a well-known VLM code are compared against wind tunnel experimental data. Section 4 includes two applications of the nonlinear VLM for wing design and optimization. The first application concerns the redesign of an UAS wing in order to increase its lift-to-drag ratio. The advantage of the new method is that it allows to modify the wing airfoil in addition to changes in wing planform. The second application concerns the determination of the performance improvements obtained through upper surface morphing for an industrial morphing wing technology demonstrator.

2. Nonlinear VLM methodology

2.1. Linear non-planar VLM formulation

Before developing the new non-linear method, a presentation of classic VLM is performed to establish the basic equations from which the new method was constructed. Within the framework of the VLM approach,[31] the singularity element is the vortex line solution of the incompressible potential flow

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