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Promising Benefits of an Active-Extrados Morphing Laminar Wing

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Nomenclature

c	=	airfoil chord, mm
E_{act}	=	energy from the actuators, J
E_{saved}	=	energy saved from the wing morphing, J
M	=	Mach number
q_∞	=	dynamic pressure, Pa
S	=	wing surface area, m^2
t	=	time duration, s
V_∞	=	freestream velocity, m/s
x	=	distance from the airfoil leading edge, mm
x_{tr}	=	transition point location from the airfoil leading edge, mm
α	=	angle of attack, deg
ΔC_d	=	drag coefficient reduction during wing morphing
ρ_∞	=	air density, kg/m^3

I. Introduction

IN AIR transport, drag reduction is often a synonym of energy saving because the energy consumption depends on the engine thrust needed to equilibrate the plane drag. Among innovative solutions, morphing technology [1] is well suited to achieve wing drag reduction. The CRIAQ (Consortium for Research and Innovation in Aerospace in Quebec) 7.1 project aims to study the feasibility of a morphing wing capable of reducing drag through laminar flow regime enhancement [2]. Because the project's credibility relies on the overall energy performance, the mechanical work requested from actuators to modify the wing profile and to improve the flow laminarity should be less important than the energy saved from the drag reduction. This paper presents a simplified efficiency analysis of such a laminar morphing wing as a path to further economic impact evaluations.

II. Design of the Morphing Wing

The morphing wing prototype is designed to be capable of modifying its extrados profile for a series of distinct flow conditions encompassing seven Mach numbers ($M = 0.2$ to 0.35, incremented by 0.025) and seven angles of attack ($\alpha = -1$ to 2 deg, incremented by 0.5 deg), which gives a total of 49 flow cases. The concept relies on an active composite structure assembled to a rigid wing body, as presented in Fig. 1. The modification of the airfoil profile occurs when shape memory alloy [3] actuators located inside the wing box apply individually controlled displacements to the flexible extrados. The overall stiffness and integrity of the experimental wing is provided by the rigid intrados. The front and rear edges of the flexible extrados are connected to the rigid intrados in such a way that ensures profile tangency continuity, accommodates shape modifications, and sustains aerodynamic forces. It results in a flush-glued joint near the leading edge and a sliding-plane link at the aft end, including a compensation spring placed between flexible and rigid structures. Finite element method sensibility analyses identified the number of actuators and the number of carbon-Kevlar plies constituting the flexible structure as the most important design variables. A total of 48 design arrangements were considered: 8 possible actuator configurations (from 0 to 7 actuators) and 6 possible ply configurations (from 3 to 8 plies). Considering maximization of the laminar flow due to wing morphing and minimization of the strain energy requested for this morphing as two design objectives, a multicriteria optimization led to the selection of a 4-ply, 2-actuator design arrangement of the active structure [4].

III. Morphing Laminar Wing Efficiency

A. Mechanical Work Provided by the Actuators

The 3-D finite element model of the active structure is built in ANSYS software using SHELL99 elements for the flexible structure and SHELL63 for the compensation leaf spring with locked rotation around the z axis, to ensure slope profile continuity. Figure 2a presents a 2-D cross section of the model. For each flow case, to enhance the laminar flow regime, previous CFD analyses [5] provided optimized displacements at each actuator point and the corresponding 2-D pressure distributions over the morphed extrados. The resulting force-stroke envelopes for both actuators covering all flow cases are presented in Fig. 2b, in which the solid and dashed rectangles correspond to the actuators located closer to the leading (act 1) and trailing (act 2) edges, respectively. The actuator force is normalized against a meter of span. It can be observed that the actuators are always in pull (or retaining) mode, as the aerodynamic suction forces prevail on the forces needed to deform the flexible extrados for all the flow cases. From the mechanical design point of view, having a unique operating mode appears to be an advantage, because one-way actuators can be used instead of two-way actuators. It is assumed that the actuators do not consume energy when the optimized shape is maintained (they are mechanically locked in this position) and that they are activated only when they return the structure to the reference profile. As an example, the actuation cycle for the flow case $M = 0.275$ and $\alpha = 0.5$ deg is presented in Fig. 2b. From the area under idealized actuation paths 1 and 2, the theoretical mechanical work required to return the structure from the morphed profile case to the reference profile can be evaluated as 5.1 and 3.2 J, respectively, with a total of $E_{act} = 8.3$ J/m of the wing span.

B. Energy Saving from Drag Reduction

To evaluate energy saving from drag reduction, both reference and morphed profiles are analyzed by the boundary-layer solver XFOIL

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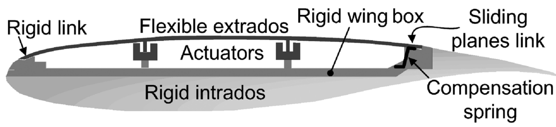
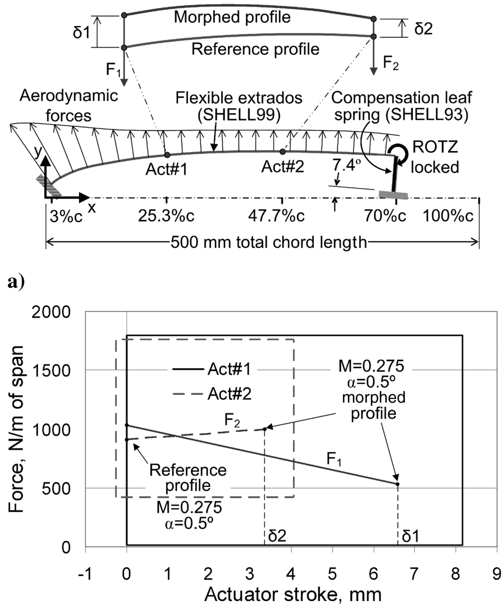


Fig. 1 Conceptual design of the morphing laminar wing.



a)

b)

Fig. 2 Structural simulation: a) numerical model of the active structure, using ANSYS software and b) working envelope of the morphing wing.

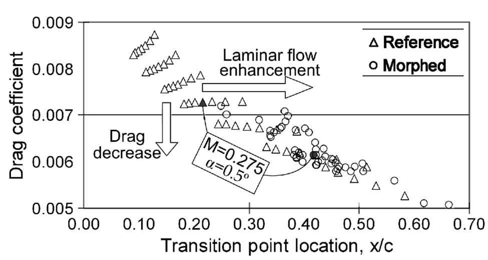


Fig. 3 Drag coefficient reduction due to laminar flow regime enhancement using the morphing laminar wing.

6.96 [6]: the drag coefficient and the location of the laminar-to-turbulent flow transition point x_{tr} are calculated for each flow case (Fig. 3). It is clear that the effect of the laminar flow enhancement (backward move of the transition point) causes significant drag reduction. For example, for the case of $M = 0.275$ and $\alpha = 0.5$ deg, a transition point for the reference profile located at $x_{\mathrm{tr}}/c = 0.22$ (with a drag coefficient of 0.0073) is pushed back to $x_{\mathrm{tr}}/c = 0.42$ (with a drag coefficient of 0.0061) when the actuators deform the flexible extrados and the optimized profile is reached.

Let us suppose that the wing profile morphs from the reference to the optimized profile and that the flight conditions corresponding to this target profile do not change over a given period of time t. The energy saved from drag reduction can then be evaluated as follows:

$$E_{\mathrm{saved}} = \Delta C_d \cdot q_\infty \cdot S \cdot V_\infty \cdot t \qquad (1)$$

Consider now a morphing wing with 0.5 m of chord and 1 m of span ($S = 0.5\ \mathrm{m}^2$) installed on an aircraft flying with an angle of attack $\alpha = 0.5$ deg for 1 min ($t = 60$ s) at a constant speed ($M = 0.275$ and $q_\infty = 5177.5$ Pa, and $V_\infty = 93.7$ m/s). If this wing now morphs to an optimized laminar profile, a laminar regime enhancement from 0.22 to $0.42 x_{\mathrm{tr}}/c$ will result in more than a 15% drag decrease (from 0.0073 to 0.0061). Given these premises, more than 16.7 kJ of energy per minute of flight can be saved. To obtain this economy, only 8.3 J of actuators' work input will be needed, which represents a tremendous potential gain.

IV. Conclusions

A finite element structural model of the active structure has been developed and an aerodynamic solver was used for the active structure efficiency evaluation. This preliminary analysis shows promising results that need to be validated through subsequent wind-tunnel testing. This evaluation, though very simplistic, traces the path to further analyses that should take more parameters into consideration (type of airplane and its engine efficiency, weight of the actuators and their energy supply systems, installation, manufacturing and maintenance cost, flight condition envelope, and frequency of morphing).

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