An energy-based design approach in the aero-structural optimization of a morphing aileron

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Abstract. This paper describes the application of an energy-based optimization procedure for the design of a morphing aileron as an alternative to replace a conventional hinged aileron. The design procedure starts with an aerodynamic shape optimization embedding skin structural constraints and energetic information. Different candidate morphing shapes able to provide reduced drag are obtained, and they differ for the required actuation level. The structural design is then performed through a dedicated multi-objective topology and sizing optimization, aimed at obtaining a structural configuration that achieves the target shape with minimum error and minimum actuation force. The energetic comparison between the designed solution and the hinged solution shows that morphing is convenient also from the energy viewpoint. Finally, a fluid-structure interaction simulation assesses the performances of the designed solution.

Introduction

Nowadays, there is a growing interest in mitigating the environmental impact of air transportation [1]. The morphing concept is one of the research topics that have the potential to improve aircraft efficiency and reduce pollutant emissions and noise [2].

The aim of this work is to design a morphing aileron and to compare its performances with a conventional hinged aileron. From the aerodynamic viewpoint, the smooth curvature change of morphing enables improved efficiency [3]. However, the morphing concept represents a valid alternative only if an overall benefit is achieved [4]. Therefore, the actuation requirement of the morphing solution is used as design objective and as performance index for validation.

The supercritical NASA SC(2)-0412 airfoil, modified to consider its shape change in the wing aileron region, is used as test case in a transonic flight condition (Reynolds=6000000, Mach=0.74). The design procedure is split in two levels. First, shape optimization is conducted, including aerodynamic analyses, skin structural constraints and energetic estimates. Second, structural optimization provides solutions according to the requirements of the previously defined target shapes. Finally, energetic and aero-structural assessments are performed.

Energy-based Shape Optimization

Parameterization technique. The Class-Shape Transformation (CST) method, specialized for morphing devices [5], is used for the airfoil identification and to introduce the morphing shape changes. The adopted approach allows the structural behavior of the morphing skin to be considered, with the analytical computation of the skin stresses from the geometrical description. The morphing shapes are parameterized using two design variables selected among the CST parameters, namely the trailing-edge equivalent rotation and the airfoil boat-tail angle variation.

Actuation energy estimate. The energy requirement for the morphing device is estimated as sum of strain energy and aerodynamic work [6]. The strain energy stored in the structure is due to the morphing deformation process and is computed analytically from the curvature variation of the skin. The aerodynamic work corresponds to the energy required to counteract the application of the aerodynamic forces during the morphing process. It can be estimated from the pressure coefficient distribution and the morphing shape change. The actuation system is assumed to be a linear sliding actuator connected to the lower skin. Assuming a linear variation of the force with the stroke, the maximum actuation force is estimated from the actuation energy.

Problem statement. The shape optimization is formulated as a multi-objective problem. Drag coefficient and actuation force are objectives to minimize. The lift coefficient is constrained to be higher than 1.15. Other constraints prevent axial stresses in the upper skin and limit the maximum curvature variation. The uncertainty associated to the structural design, namely the thickness distribution of the skin, is also considered in the optimization by parametrically solving the optimization problem for different thickness values. Response surface models of the objective functions and constraints are built to perform the optimization.

Response surfaces. Lift and drag coefficients are computed with Reynolds-averaged Navier-Stokes (RANS) equations, solved in SU2 [7]. CST is used to compute strain energy, aerodynamic work, actuation energy and force. All these outputs are computed for a Latin hypercube sample in the space of the design variables. These simulated values are used to construct response surface models through Radial Basis Function (RBF) interpolation.

Shape optimization results. The multi-objective optimization based on response surfaces is performed for four thicknesses values, resulting in several Pareto fronts, which are reported in Fig. 1. Different morphing solutions can provide reduced drag, but they differ for the actuation level required to achieve the morphing shape. Three candidate shapes are selected for the subsequent steps of analysis and design.

Aerodynamic comparison with the hinged aileron. The aerodynamic performances of the selected optimal shapes are compared with the hinged aileron rotated of 9.7 deg, which corresponds to the target lift coefficient requirement. The rigid solution is characterized by higher drag, resulting in lower aerodynamic efficiency at each angle of attack.

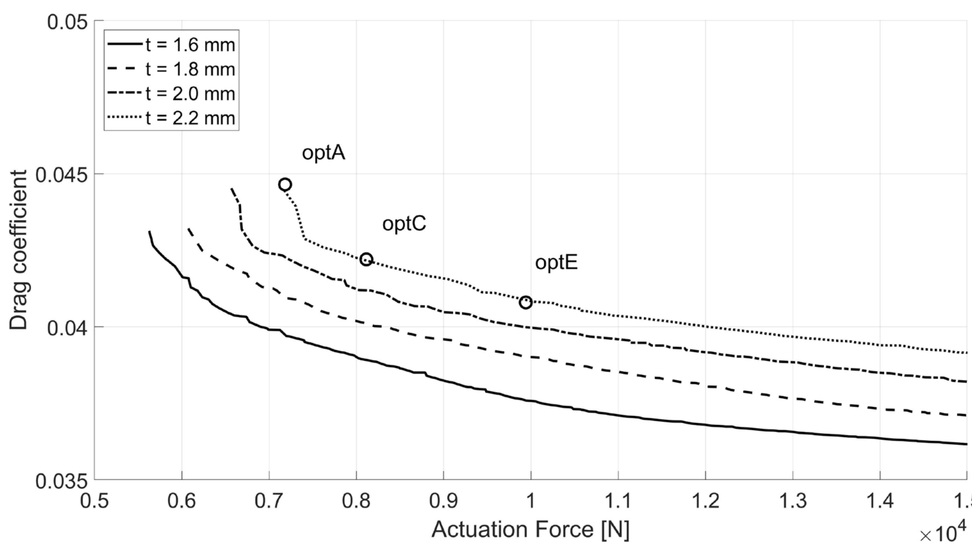

Figure 1: Pareto fronts from the shape optimization for different values of skin thickness t and equal value of target C_L=1.15.

Structural Topology and Sizing Optimization

The structural design of the morphing trailing-edge is based on a medium-fidelity FEM model consisting of a skin section and some internal beams connected to upper and lower skin.

Problem statement. A dedicated multi-objective genetic algorithm is used for the topology and sizing optimization. The design variables describe both the topology (beam attachment points, beam existence) and the sizing (in-plane dimensions of skin and beams). Different objectives are minimized: i) the least-square error (LSE) between the target shape and the morphing shape of the actuated device subject to the aerodynamic loads of the target shape; ii) the actuation force to achieve the morphing shape; iii) the LSE between the undeformed configuration and the undeployed deformed shape under the baseline aerodynamic loads.

Structural design results. The adopted optimization enables to achieve the target shape with minimum error and minimum force. The process is repeated for the three candidate shapes.

Aerodynamic validation. Aerodynamic analyses of the achieved morphing shapes are performed to evaluate if the target lift coefficient is achieved. When this is not guaranteed (*optC*, *optE*), a slightly increase of the actuator stroke allows the target lift coefficient to be met. The three deformed morphing shapes are compared with the hinged shape in Fig. 2.

Structural validation. Strain in the structure is below 0.5%, as depicted in Fig. 3 in case of solution *optE*.

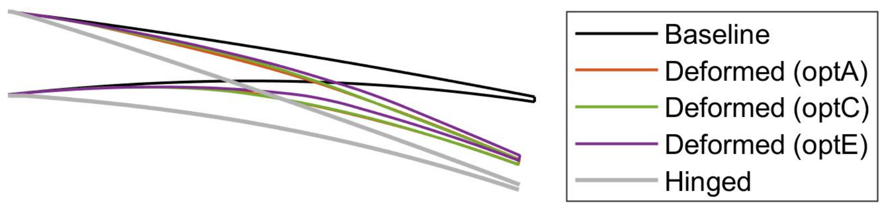

Figure 2: Morphing shapes and hinged shape corresponding to target C_L=1.15.

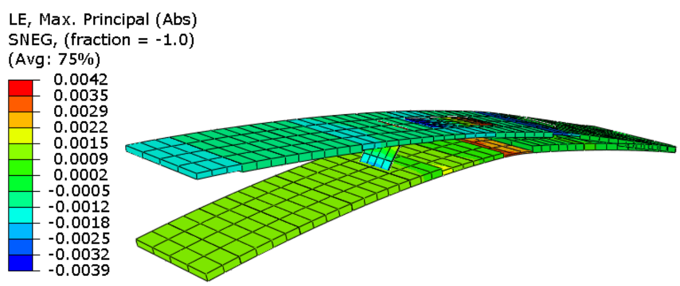

Figure 3: Strain distribution in the structure for solution optE.

Actuation Energy Evaluation

The designed structural solutions that guarantee the target lift coefficient are compared with the hinged solution from the actuation energy viewpoint. The actuation energy for the morphing solutions can be divided in a structural contribution (due to the strain energy) and an aerodynamic contribution (due to the aerodynamic loads), as reported in Fig. 4. The morphing results are compared with the hinged energy result, computed from hinge moment and aileron rotation, and totally due to aerodynamic loads. Although there is a strain energy contribution associated with the morphing process, the actuation energy for morphing solutions is lower than the energy required by hinged solution. This is possible because morphing solutions can achieve the target lift coefficient with smaller trailing-edge equivalent rotation with respect to the rigid rotation of the conventional aileron. Consequently, reduced drag is also achieved.

Performance Assessment

As final validation, a fluid-structure interaction (FSI) analysis, coupling RANS analyses and nonlinear structural analyses, is performed to evaluate how the aerodynamic performances are affected by the structural compliance. This FSI analysis shows that the morphing shape can be achieved as expected from FEM analyses, with negligible differences in the deployed configuration, that do not compromise the requested lift coefficient increment. However, the structural compliance has a small impact on the baseline configuration of the airfoil.

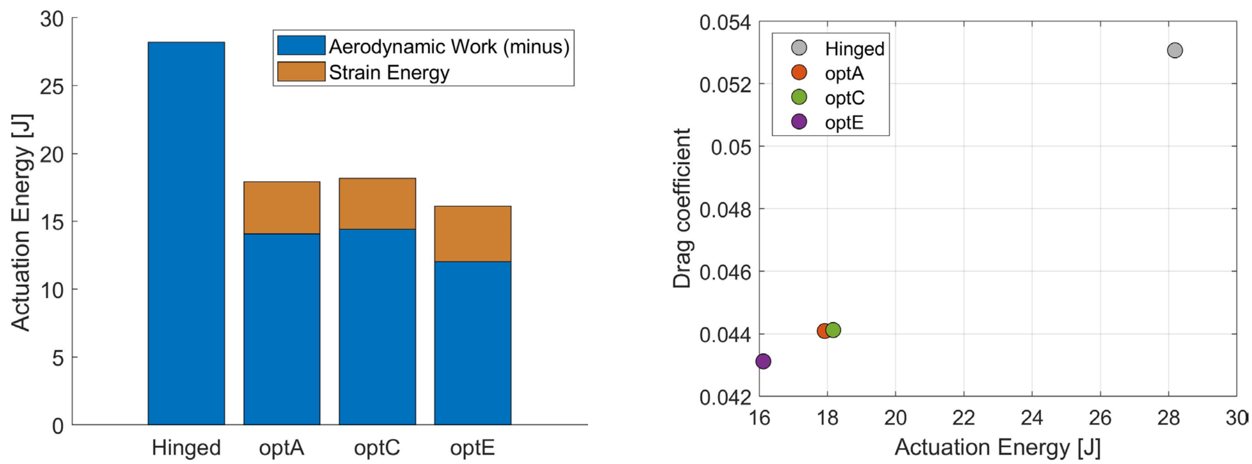

Figure 4: Actuation energy and drag coefficient comparison between morphing and hinged aileron.

Conclusions

This paper has presented the optimum design of a morphing aileron and the comparison of its performances with a corresponding hinged aileron. The proposed energy-based approach has proved successful in providing morphing solutions characterized by enhanced aerodynamic and energetic efficiency with respect to the conventional hinged solution.

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