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Design of a transonic wing with an adaptive morphing trailing edge via aerostructural optimization

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A R T I C L E I N F O

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A B S T R A C T

Novel aircraft configurations and technologies like adaptive morphing trailing edges offer the potential to improve the fuel efficiency of commercial transport aircraft. To accurately quantify the benefits of morphing wing technology for commercial transport aircraft, high-fidelity design optimization that considers both aerodynamic and structural design with a large number of design variables is required. To address this need, we use high-fidelity aerostructural that enables the detailed optimization of wing shape and sizing using hundreds of design variables. We perform a number of multipoint aerostructural optimizations to demonstrate the performance benefits offered by morphing technology and identify how those benefits are enabled. In a comparison of optimizations considering seven flight conditions, the addition of a morphing trailing edge device along the aft 40% of the wing can reduce cruise fuel burn by more than 5%. A large portion of fuel burn reduction due to morphing trailing edges results from a significant reduction in structural weight, enabled by adaptive maneuver load alleviation. We also show that a smaller morphing device along the aft 30% of the wing produces nearly as much fuel burn reduction as the larger morphing device, and that morphing technology is particularly effective for high aspect ratio wings.

1. Introduction

Increased awareness of environmental concerns and fluctuations in fuel prices in recent years have led the aircraft manufacturing industry to push for improved aircraft fuel efficiency. Compared to the rapid improvements in aircraft fuel efficiency seen between 1960 and 1990, the rate of improvement in recent decades has been more moderate. Decades of experience and design refinement have left only relatively small improvements to be made on conventional wing and tube configurations. The combination of increased interest in reducing fuel burn and the recent plateau of fuel burn improvements with a conventional configuration has pushed aircraft manufacturers and researchers to consider new technologies and configurations that offer the potential for further efficiency improvements. In the long term, new unconventional aircraft configurations offer promising potential; however, they are likely a few decades from commercial availability. There are also a number of technologies that are closer to entering the market and offer efficiency improvements on conventional configurations, like tow-steered composites [1] and functionally graded materials [2].

Another such technology is adaptable morphing trailing edge, also known as adaptive compliant trailing edge, or simply adaptive trailing edge [3]. Companies such as FlexSys have already developed such devices [4–6] and have performed flight tests in collaboration with NASA and the U.S. Air Force Research Laboratory [7]. This technology offers the potential to create wings that can actively adapt to flight conditions, enabling engineers to design the wing shape and sizing with much more robust performance with respect to the flight conditions. Another variant of this technology is the variable camber continuous trailing edge flap, which changes the camber using three segments that rotate rigidly [8,9].

Various studies have reviewed morphing mechanisms [10–13] and explored and reviewed the benefits of applying this technology to wing design [14–18]. In the late nineties, Hanselka [19] and Monner et al. [20] outlined the aerodynamic benefits associated with morphing trailing edge devices and offered designs for morphing mechanisms. More recently, Molinari et al. [21,22] explored the potential of the technology using a multidisciplinary optimization approach considering mission, aerodynamic, materials, and structural disciplines. That work used low fidelity models and therefore was unable to capture the effects of small shape changes, which have been shown to be crucial in transonic aerody-

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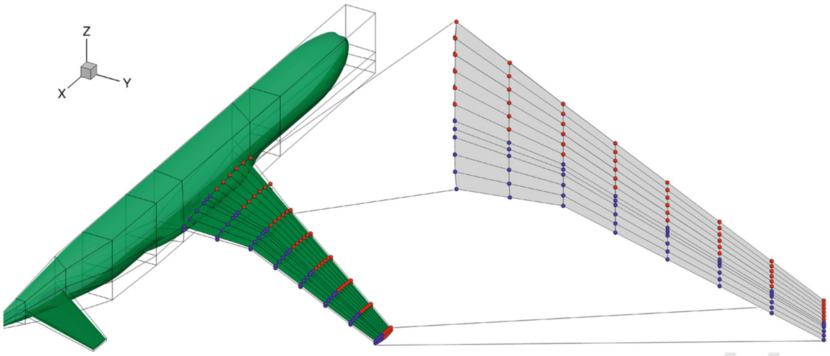

Fig. 1. The control points in this shape parametrization are aligned with 30, 35, and 40% of the chord. Allowing the 4 aft-most rows of design variables to move results in a morphing device spanning the area enclosed by the blue (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.) control points.

namic performance [23]. Reynolds-averaged Navier–Stokes (RANS) simulations are required to capture the viscous and compressibility effects in that flight regime. Lyu and Martins [24] used RANS-based aerodynamic shape optimizations to design a wing with a morphing trailing edge showing drag reductions between one and five percent, depending on the flight condition. Wakayama et al. [25] found similar results in their work considering morphing devices on three different aircraft configurations. Other studies have also considered dynamic aeroelastic constraints [26]. Multidisciplinary design optimization (MDO) provides the computational approach to make the most of these technologies [27].

We have previously used MDO coupling high-fidelity models of the aerodynamics and structures to evaluate a wing with a morphing trailing edge at a single cruise point [28], showing that the morphing trailing edge can drastically affect the wing spanwise lift distribution. In the work presented herein, we seek to build off of these previous results by expanding the number of flight conditions where the performance of the wing is considered. The main advantage of morphing trailing edge technology is its ability to adapt a wing to changing flight conditions, so we expect multipoint analysis to provide better opportunities for the morphing trailing edge to improve performance. The inclusion of structural analysis is also important, as structural deflections will vary at different flight conditions, providing further opportunity for the morphing trailing edge to improve performance. In this work, we assume an ideal morphing mechanism that can achieve the specified shape, where the weight of the mechanism is comparable to that of conventional control actuators. While this is not a realistic assumption, these studies provide an upper bound on the benefits of morphing technologies and open the door for more detailed studies using high-fidelity aerostructural design optimization.

This paper is organized as follows: Section 2 describes the computational tools used in this work. Section 3 defines the optimization problems solved in this work, including baseline configurations, multipoint stencil definitions, and an overview of the optimization parameters. Section 4 presents the optimization results, followed by the conclusions in the last section.

2. Overview of numerical methods

In this section, we discuss the numerical analysis and design optimization algorithms used in this work. The numerical algorithms are implemented in components of the MACH (MDO for Aircraft Configurations with High fidelity) framework [29]. The tools outlined herein have been used on a wide variety of aerodynamic [23,30,31] and aerostructural aircraft design optimization problems [32–34] as well as optimizations of wind turbine blades [35] and hydrofoils [36].

2.1. Geometric parametrization

Geometric shape changes are parametrized using a Free Form Deformation (FFD) approach [37], a technique that is also used frequently in computer graphics to generate deformations of solid geometries [38]. The approach implants the solid geometry within an outer hull that is parametrized with a series of control points. The control points generate deformations of the encompassing volume, which are interpolated onto the geometry. The interpolation generates a region of influence spanning two control points in each (i, j, and k) parametric direction and provides smooth deformations that are defined with a relatively small number of design variables. Aggregating control points also allows for the creation of larger-scale global design variables such as chord, span, and twist. An example of an FFD used for a morphing trailing edge optimization is shown in Fig. 1.

Note that the FFD does not have a uniform distribution of control points along the (chord-wise) x-direction. Instead, there is a grouping of control points near the leading edge of the morphing region. This control point distribution allows for simple implementation of the morphing trailing edge. The subset of the FFD control points on the aft region of the wing is given additional freedom at each flight condition, allowing the wing to assume different shapes at different flight conditions. The FFD is a tri-variate B-spline volume, so the geometric shape changes produced by a single control point moving are continuous changes restricted to a region spanning *exactly* two control points in each direction. Using this feature of the parameterization, we define the size of the morphing device using control point placement. The increased control point density near the boundary of the morphing region provides a parameterization that can generate smooth and rapid transitions between the morphing and fixed regions.

The use of FFD to parameterize morphing is not typical in the literature. Most morphing studies start with an assumed mechanism and simulate morphing using the restricted design space provided by that specific mechanism [21,25,26]. Examples of such morphing shape design spaces include a number of rigid rotations or a series of spanwise polynomial deformation profiles [9]. The morphing deformations produced using FFDs in this work represent a wider design space. This less restrictive parameterization permits a wide variety of morphing shapes, which when coupled with gradient-based optimization allows the exploration of the potential of morphing technology, rather than the potential of a specific morphing mechanism. As such, the optimal morphing shapes presented in this paper are mechanism-independent optimal shapes. This approach is useful for quantifying the potential of general morphing technology, but it also informs the design of morphing mechanisms. Mechanisms capable of producing the morphing shapes found in the optimizations herein can provide the

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