Nonlinear Modeling and Aeroelastic Analysis of an Adaptive Camber Wing

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Static aeroelastic analysis of an adaptive camber wing subjected to low-speed subsonic flow is presented. In finite element modeling follower forces, geometric nonlinearity, and contact definitions are included to accurately integrate a previously designed hingeless control surface into the wing. Camber variation is controlled at six spanwise stations using actuators for which actuation force magnitudes are determined iteratively using linearized influence coefficients. Flow solutions are obtained using a high-order panel method, and aeroelastic coupling is performed using the in-house code SAMOA. For morphed-wing configurations, induced drag is reduced by creating washout.

By conducting static aeroelastic analysis actuation, force magnitudes are determined and favorable aerodynamic effects are identified. Results indicate that use of a nonlinear structural model is essential in capturing the stiffening behavior observed during application of spanwise variable camber.

I. Introduction

The requirement to adapt to changing flight conditions has been essential since the early days of aviation. Use of systems such as high-lift devices and variable-sweep wings enable conventional aircraft to improve performance within their designated operational range. However, since aircraft are usually optimized for a limited number of discrete design points, the performance gains cannot be maximized within the full flight envelope [1,2]. Morphing technology provides the means for performance optimization for the complete flight envelope.

Although the definition of morphing still varies among the technical community, it is generally accepted that morphing corresponds to a state change that targets efficiency and adaptability. A more recent definition declares morphing as “real-time adaptation to enable multipoint optimized performance” [3].

During morphing, air vehicles exhibit local or global transformations using smart and/or conventional actuators [3,4]. In some of the most recent studies [5–17] the use of unconventional designs featuring mechanisms or compliant structures that employ composite or elastomer-type materials appears to be the most common point. To define morphing and to quantify the benefits a formal assessment process [18] may be adopted.

Morphing aircraft can accommodate large changes in wing planform area, sweep angle, and span [8,9] to have multiple roles and fulfill conflicting performance requirements. Another form of morphing involves wings with variable camber [1,2,4–7,10,14,17], where smooth aerodynamic surfaces are created to accommodate laminar flows [2,10]. By applying spanwise camber variations, aerodynamic loads can be redistributed adaptively during the flight to balance the weight decrease due to fuel burn, minimize drag, and reduce wing root bending moments [1,2]. The potential increase in lift-to-drag ratio varies between 3 to 10% for a typical transport-type aircraft during cruise [1].

In most applications of wings with variable camber, conventional structures are replaced or modified to increase the flexibility in a controlled manner. For instance, the belt-rib [5] approach uses multiple spokes that permit camber variations to replace the traditional ribs. The compliant trailing-edge flap developed by Flexsys, Inc., [10] uses elasticity to recontour the upper and lower skins. Analysis and flight tests have shown that this lightweight and low-power design can maintain long laminar runs and low drag, even with significant camber variations.

As an alternative to compliant structures, rotating (or deformable) ribs of either single-piece [4,6,7,17] or multiple segments [1] combined with mechanisms are also used. When ribs are rotated, skins flex and sliding is facilitated by the presence of open trailing edge. These features reduce structural stresses and actuation force magnitudes.

In this study, the nonlinear finite element modeling and analysis are done using MSC PATRAN [19] and MD NASTRAN [20], respectively. A code is developed to perform static aeroelastic analyses of an adaptive camber wing (ACW). Steady-state aerodynamic loads are calculated using the high-order panel code PAN AIR [21]. For an accurate representation of the fluid–structure interface, local shape functions are used to interpolate displacements and pressures. By using an iterative process, which employs linearized influence coefficients, actuation force magnitudes are calculated for morphing wings subject to spanwise camber variation.

II. Concept Description and the Structural Model

Figure 1 shows the ACW with the full-span hingeless control surface (HCS) and NACA 4412 airfoil section. A rectangular planform with 0.5 m chord and 1.5 m semispan is chosen to simplify the models and better interpret the results. The HCS design is based on the concept by Seber et al. [17] that exploits controlled structural flexibility to accommodate camber variations. Some unconventional elements such as a semi-open trailing edge, i.e., only sliding in chordwise direction is permitted, and cutout ribs are featured. However, no major structural modifications are required at the traditional semimonocoque torque box, and the ACW is considered to be made out of standard aluminum 2024-T3 alloy.

To apply camber variations, servo actuators initiate sliding at the guide-slip assemblies (GSAs) via push-rods that are connected to the cutout ribs (see Fig. 2). Sliding flexes the upper and lower skins between the torque box and the cutout ribs. GSAs maintain integrity by preventing the separation of lower and upper skins at the trailing edge, and they are basically prismatic joints. The two main components (namely, the cutout ribs and the tracks) are rigidly connected to upper and lower skins, respectively, but not to each other. The current model features GSAs that are aligned with the main ribs that are 28 cm apart.