Aerospace Science and Technology ••• (••••) •••–•••

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Aerospace Science and Technology

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Optimum distributed wing shaping and control loads for highly flexible aircraft

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ARTICLE INFO

Article history:
Received 6 October 2017
Received in revised form 25 April 2018
Accepted 24 May 2018
Available online xxxx

Keywords:
Wing shaping control
Optimum wing geometry
Distributed control load
Highly flexible aircraft

ABSTRACT

In highly flexible aircraft, the large structural slenderness associated to their high-aspect-ratio wings, while bringing challenges to the design, analysis, and control of such aircraft, can be pro-actively exploited for improving their flight performance, resulting in mission-adaptive morphing configurations. This paper studies the optimum wing bending and torsion deformation of highly flexible aircraft, with distributed control loads along the wing span to achieve the optimum wing geometry. With the goal of improving flight performance across the entire flight regime, a modal based wing shaping optimization is carried out, subject to the requirement of trim and control cost limitation. While a single objective of the minimum drag can be used to find the optimum wing geometry, this paper further considers a trade-off between flight efficiency and structural integrity. In this trade-off study, a multi-objective optimization is formulated and performed, targeting for both minimizing the drag to improve flight efficiency and reducing the gust-induced wing bending moment to enhance the structural integrity. Finally, this paper explores the minimum control cost for different targets of combined flight efficiency and structural integrity. This paper provides not only an efficient way to search for the desired wing planform geometry at a given flight condition but also insights of the required control effort that is necessary to maintain the wing geometry.

1. Introduction

The improvement of aircraft operation efficiency needs to be considered over the whole flight plan, instead of a single point in the flight envelope, since the flight condition varies in a flight mission. Therefore, it is natural to employ morphing wing designs so that the aircraft can be made adaptive to different flight conditions and missions. At the advent of recent development in advanced composites as well as sensor and actuator technologies, in-flight adaptive wing/airfoil morphing is now becoming a tangible goal. Traditionally, discrete control surfaces were used to re-distribute the aerodynamic loads along the wing span during the flight, to tailor the aircraft performance. However, the deflection of discrete control surfaces may increase the aerodynamic drag. A practical alternative is to introduce conformal wing/airfoil shape changes for the aerodynamic load control. In addition, the flexibility associated with the morphing wing structures may be pro-actively utilized to improve the aircraft performance. The active aeroelastic tailoring techniques will allow aircraft designers to take advantage of the wing flexibility to create the desired wing load distribution according to the mission requirement, to improve overall aircraft operating efficiency and performance, without using the traditional discrete control surfaces. The utilization of these concepts is predicated upon the optimum shape being known and a control system which can produce this wing shape.

The question of determining the optimum wing shape has been studied in depth. Recently, Chen et al. [1] investigated the effects of various trim conditions on the aerodynamic shape optimization of the Common Research Model wing-body-tail configuration. Using a free-form distribution for the wing geometry coupled with a RANS solver for the aerodynamics, they studied the impact of a trim constraint on the optimization process. Through a series of optimizations utilizing the trim conditions at varying points in the design process, they concluded that considering the trim during optimization yields the best performance. In a similar study, Lyu and Martins [2] performed an aerodynamic optimization of the trailing edge of a wing. Their optimization showed the drag reductions (including induced drag, friction drag and wave drag of a full aircraft planform) with shape optimization of either the entire wing or just the trailing edge. Previtali et al. [3] used a concurrent

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https://doi.org/10.1016/j.ast.2018.05.045
1270-9638/

Please cite this article in press as: J.R. Hammerton et al., Optimum distributed wing shaping and control loads for highly flexible aircraft, Aerosp. Sci. Technol. (2018), https://doi.org/10.1016/j.ast.2018.05.045

Nomenclature

Symbol	Description	Unit
a	Centrifugal acceleration	m/s^2
B	Body-fixed frame	
b_c	semi-chord of airfoil	m
$\mathbf{B}^F$, $\mathbf{B}^M$, $\mathbf{N}^g$	Influence matrices for aerodynamic force, moment, and gravity force	
$\bar{\mathbf{B}}_F$, $\bar{\mathbf{B}}_B$	Components of influence matrix for **u**	
$\mathbf{B}_u^f$, $\mathbf{B}_u^m$	Influence matrices in control loads	
$\mathbf{C}_{FF}$, $\mathbf{C}_{FB}$, $\mathbf{C}_{BF}$, $\mathbf{C}_{BB}$	Components of generalized damping matrix	
$\mathbf{C}^{GB}$	Rotation matrix from body frame to global frame	
C_1, C_2, C_3, C_4	Optimization constraints	
d	distance of midchord in front of beam reference axis	m
E_{max}, R_{max}	Maximum endurance and range of aircraft	s, m
$\mathbf{F}^a$, $\mathbf{M}^a$	Aerodynamic force and moment on wing sections	N, N·m
$\mathbf{F}_u^{pt}$, $\mathbf{M}_u^{pt}$	Complete points loads due to **u**	
$\mathbf{F}_1$, $\mathbf{F}_2$, $\mathbf{F}_3$	Matrices for inflow states differential equitation	
G	Global or inertial frame	
$\mathbf{g}$	Gravitational acceleration vector	m/s^2
$\mathbf{J}$	Jacobian matrices relating independent and dependent variables	
$\mathbf{K}_{FF}$	Generalized stiffness matrix	
L, D, W	Total lift, drag, and weight of aircraft	N
l_{mc}, m_{mc}, d_{mc}	Aerodynamic lift, moment, and drag in local aerodynamic frame about midchord	N/m
$\mathbf{M}_{FF}$, $\mathbf{M}_{FB}$, $\mathbf{M}_{BF}$, $\mathbf{M}_{BB}$	Components of generalized inertia matrix	
M_y^g	Gust-induced aerodynamic bending moment	N·m
$\mathbf{P}_B$	Inertial rigid-body position of aircraft	m
$\mathbf{Q}$	Tuning matrix for control cost	
$\mathbf{q}$	Trim or design variables	
R	Radius of turning path	m
$\mathbf{R}_F$, $\mathbf{R}_B$	Flexible and rigid-body components of generalized load vector	
$\mathbf{R}_F^u$, $\mathbf{R}_B^u$	Generalized loads due to **u**	
$\mathbf{r}_F$, $\mathbf{r}_B$	Residuals of equilibrium equation	
$\mathbf{T}$	Thrust force vector	N
U_c	Control cost	
U_∞	Flight speed	m/s
$\mathbf{u}$	Distributed wing shaping control force vector	
w	Wing node-fixed local frame	
w_g	Gust velocity	m/s
$\dot{y}$, $\dot{z}$, $\ddot{z}$, $\dot{\alpha}$, $\ddot{\alpha}$	Airfoil motion variables in local aerodynamic frame	
α_B	Aircraft pitching angle	rad
α_g	Gust-induced angle of attack	rad
$\boldsymbol{\beta}$	Rigid-body velocity of aircraft	m/s, rad/s
$\boldsymbol{\varepsilon}$	Complete strain vector of aircraft	
$\boldsymbol{\varepsilon}^0$	Initial strain of aircraft	
$\boldsymbol{\varepsilon}_e$ $(\varepsilon_x, \kappa_x, \kappa_y, \kappa_z)$	Elemental strain vector and its components	
$\boldsymbol{\zeta}$	Quaternion	
η	Magnitude of mode shapes	
$\boldsymbol{\lambda}$	Inflow states for unsteady aerodynamics	
λ_0	Induced velocity due to wake	m/s
ξ_1, ξ_2	Tuning parameters in multi-objective optimizations	
ρ_∞	Air density	kg/m^3
$\boldsymbol{\Phi}$	Linear mode shape of aircraft	
φ_B	Aircraft bank angle	rad

approach to optimize a 3-D morphing wing. In this work, rolling moment, weight, and maneuver aerodynamic drag were considered at different flight speeds, where the wing performances were compared with those of a conventional wing. Taking the optimization a step further requires the development of a realistic system capable of producing the optimum shape that is suitable for a given flight condition. This concept was highlighted in Nguyen et al. [4], where the design of the Variable Camber Continuous Trailing Edge Flap (VCCTEF) is introduced. In addition, an optimization is performed to determine the deflection angles required throughout the trailing edge to improve the flight performance.

Many wing morphing technologies have been developed over the years as the materials and fabrication methodologies have advanced. Molinari et al. [5] presented wind tunnel and flight tests of a morphing wing built by using compliant mechanisms and piezoelectric actuators. In Nguyen et al. [6] the principles of aerodynamic shape optimization and morphing wing structures were explored. The optimization process led to the development of the VCCTEF, which was a novel concept for improving aircraft performance by drag reduction. A further study of the VCCTEF wing model was conducted by Nguyen and Ting [7], where they performed a flutter analysis of the mission-adaptive wing. The methodology included a vortex-lattice aerodynamic model coupled with a finite element structural dynamic model. Urnes et al. [8] provided an updated review of the development, design, and testing of the VCCTEF project. Under the support of the U.S. Air Force Research Laboratory, FlexSys, Inc. developed the Mission Adaptive Compliant Wing (MAC-Wing) to test and evaluate its performance. The adaptive trailing edge flap technology was combined with a natural laminar flow airfoil and tested on the Scaled Composites White Knight aircraft. The testing suggested fuel saving, weight reduction, and improved control authority [9,10]. In an effort to move from an adaptable trailing edge to a completely adaptable wing structure, the Cellular Composite Active Twist Wing was designed and tested in Cramer et al. [11], showing promising results. A scaled airplane model was built, which incorporated active twist wings and was compared to a similar rigid model with traditional control surfaces in wind tunnel tests. The active twist wings showed similar capabilities for symmetric and asymmetric movements as well as added benefits in the stall mitigation. An overview of the process used to design the composite lattice-based cellular structures for active wing shaping was presented in Jenett et al. [12], in which they presented a detailed approach for designing a low density and highly compliant structure.

Although both the optimization process and the morphing technology have improved, there is a need for a complete system, in which a robust controller may actuate and maintain the wing members to the desired optimum shape throughout the flight envelope. The controller may also perform the required maneuver and vibration control during the flight. Most current optimization schemes utilize a CFD aerodynamic model coupled with discrete structural points as design variables. These methods produce promising results. However, when optimization is performed over an entire flight plan, this approach could be very time-consuming. Moreover, these methods consider the detailed wing shape rather than the wing bending and torsions associated with highly flexible, large aspect-ratio wing members. Recent developments of morphing technologies such as the Cellular Composite Active Twist Wing take advantage of the flexible nature of high-aspect-ratio wings. Therefore, it is natural to develop an optimization scheme that mainly considers the bending and torsion of the high-aspect-ratio wings of high-altitude, long-endurance aircraft. This concept was implemented in Su et al. [13], which utilized a modal based optimization approach in determining the best feasible wing shape

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