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Adaptive and neural control of a wing section using leading- and trailing-edge surfaces ☆

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Abstract

This paper treats the question of control of nonlinear aeroelastic responses of a prototypical wing section with structural nonlinearity using leading- and trailing-edge control surfaces. It is assumed that all the aerodynamic, structural and inertia parameters are unknown to the designer. As such the limitation of a recent control design reported in the literature, which requires complete knowledge of aerodynamic derivatives and inertia parameters, is removed. An adaptive controller and a neural control system are designed for the trajectory control of the plunge displacement and pitch angle. For the derivation of the adaptive control law, a linearly parameterized model is used but the neural controller is designed by treating the stiffening-type structural nonlinearity as an unstructured function (not parameterizable). It is shown that the adaptive and neural controllers accomplish trajectory control in the closed-loop system. Simulation results are presented which show that these controllers are effective in regulating the nonlinear responses to the origin in the state space in spite of large model uncertainties. Moreover unlike the model with a single trailing-edge surface, two control surfaces provide flexibility in shaping both the plunge and pitch responses.

Keywords: Aeroelastic system; Adaptive control; Neural control; Nonlinear system

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1. Introduction

Aeroelastic systems exhibit a variety of phenomena including instability, limit cycle oscillation (LCO), and even chaotic vibration [5,6,8,17,31] due to the interaction of aerodynamic, elastic and inertial forces. Active control of aeroelastic instability is an important problem. An excellent survey paper by Mukhopadhyay [19] provides historical perspective on analysis and control of aeroelastic systems. Several studies have been made to analyze the nonlinear responses of aeroelastic systems and design active control systems for avoiding instability [1–4,12–15]. Study of nonlinear responses using computational and experimental methods has been considered in [24]. A digital adaptive design for a linear aeroservoelastic model has been presented in [7, 9]. A benchmark active control technology (BACT) wind-tunnel model has been designed for the study of nonlinear aeroelastic behavior at the NASA Langley Research Center [2,23,29] and various active control algorithms have been developed for flutter suppression [18,29]. Control systems for the control of aeroelastic responses using the classical and minmax methods [18] and robust passification technique [12] have been obtained. For the BACT wind-tunnel model, neural-network gain-scheduled flutter control systems have been designed and experiments have been performed [22]. In the research work of [22], the neural network has been trained using backpropagation to output the two numerator, the four denominator coefficients and the overall gain of the linear filter (controller) as functions of Mach number and the dynamic pressure.

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Nomenclature

a	nondimensionalized distance from the midchord to the elastic axis
b	semichord of the wing
c_h	structural damping coefficient in plunge due to viscous damping
c_α	structural damping coefficient in pitch due to viscous damping
c_l	wing section lift coefficient
$c_{l\alpha}$	$\partial c_l/\partial\alpha$
$c_{l\beta}$	$\partial c_l/\partial\beta$
$c_{l\gamma}$	$\partial c_l/\partial\gamma$
$c_{m-c/4}$	wing section moment coefficient at quarter-chord
$c_{m\alpha}$	$\partial c_{m-c/4}/\partial\alpha$
$c_{m\beta}$	$\partial c_{m-c/4}/\partial\beta$
$c_{m\gamma}$	$\partial c_{m-c/4}/\partial\gamma$
μ, L_i	control gain and weighting matrices
h	plunge displacement
I_α	mass moment of inertia about the elastic axis
k_h	structural spring constant in plunge
k_{α_i}	structural spring constant in pitch
m_t	mass of the plunge-pitch system
m_w	mass of the wing
M_i, B_0, g_0	system matrices
S	stable manifold
s_p	span
U	freestream velocity
u	control input
V, W	Lyapunov functions
x	state vector
x_α	nondimensionalized distance measured from the elastic axis to the center of mass
$y, y_r, \tilde{y}$	output, reference output and tracking error
α	pitch angle
α_r, h_r	reference pitch angle and plunge displacement
γ, β	leading- and trailing-edge surface deflection
λ	stable manifold parameter
$\varepsilon(\alpha)$	approximation error
$\theta, \theta_u, w, \eta$	unknown parameters
$\hat{\theta}, \hat{\theta}_u, \hat{w}, \hat{\eta}$	parameter estimates
Φ, Ψ, Φ_u	regressor matrices
ρ	air density

Researchers have given considerable attention to the presence of limit cycle oscillations, which are attributed to structural nonlinearity in the aeroelastic system [4,5,13]. A dual input describing function method has been used for the prediction of LCO's for an aeroelastic system with unsteady aerodynamics [10]. An aeroelastic apparatus has been constructed for laboratory experiments and the effect of nonlinear structural stiffness on nonlinear responses have been examined [13–15]. For this model, control systems have been designed using linear control theory [4], feedback linearizing technique, and adaptive control strategies [13–15, 30]. An aeroelastic model with unsteady aerodynamics has been considered for control in [3]. The state-dependent Riccati equation method has been used for the stabilization of LCO in [25].

The aeroelastic models considered in [4,13,14,25,30] have a wing section with a single trailing-edge control surface. In a recent paper, Platanitis and Strganac [20] have considered a wing model with leading- and trailing-edge control surfaces and designed an adaptive control system for the control of nonlinear responses. It has been shown that unlike the wing section with a single trailing-edge surface, enhanced performance is achieved by introducing the additional leading-edge control surface. It is well known that for the model with a single control surface, trajectory control of either the plunge displacement or the pitch angle (but not of both) can be achieved by the feedback linearization (inverse control) technique [13,14] and there exist zero dynamics describing the residual motion in the closed-loop system. Zero dynamics describe the motion of the system when the controlled output variable (pitch angle or plunge displacement for the single surface case) is constrained to be zero. In the closed-loop system with an inverse controller [13–15,30], the asymptotic behavior of the aeroelastic system depends on the stability property of the zero dynamics. The zero dynamics of the aeroelastic system depend on the model parameters including the freestream velocity and the location of the elastic axis [15]. For certain values of these parameters, zero dynamics can be weakly stable and in such cases, feedback linearizing controllers give sluggish flutter control using a single surface. An important advantage of use of two control surfaces is that one can design an exact feedback linearizing control and there does not exist zero dynamics. The adaptive design of [20] is based on the assumption that only the stiffness parameters are unknown, but wing mass and inertia as well as all the aerodynamic parameters are known to the designer. Of course, it is more realistic to assume that the remaining parameters of the model are also unknown. Especially the assumption that the aerodynamic parameters are exactly known is quite restrictive. As such it is desirable to develop control laws for the control of the aeroelastic system with two control surfaces to alleviate the stringent requirement on the knowledge of system parameters.

The contribution of this paper lies in the design of an adaptive as well as a neural control system for the control of a typical wing section equipped with leading- and trailing-edge control surfaces. For the design, it is assumed that all the system parameters (mass, inertia, structural and aerodynamic parameters) are unknown. This assumption requires that one must treat the control input influence ma-