

$\mathcal{L}_1$ Adaptive Flutter Suppression Control Strategy for Highly Flexible Structure

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ABSTRACT

The aim of this work is to apply an innovative adaptive $\mathcal{L}_1$ techniques to control flutter phenomena affecting highly flexible wings and to evaluate the efficiency of this control algorithm and architecture by performing the following tasks: i) adaptation and analysis of an existing simplified nonlinear plunging/pitching 2D aeroelastic model accounting for structural nonlinearities and a quasi-steady aerodynamics capable of describing flutter and post-flutter limit cycle oscillations, ii) implement the $\mathcal{L}_1$ adaptive control on the developed aeroelastic system to perform initial control testing and evaluate the sensitivity to system parameters, and iii) perform model validation and calibration by comparing the performance of the proposed control strategy with an adaptive back-stepping algorithm. The effectiveness and robustness of the $\mathcal{L}_1$ adaptive control in flutter and post-flutter suppression is demonstrated. Results and discussion will follow with pertinent conclusions and future outlooks.

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INTRODUCTION

Analysis and control of aeroelastic phenomena affecting different type of slender structure is the main objective of the investigators' A2-Net-Team-Project funded by the European Community under the FP7 Marie Curie Grant No. 269190. Of great interest, because of its criticality, flutter and adaptive control strategies to suppress nonlinear dynamic aeroelastic instabilities are investigated. Although flutter boundaries in most cases can be theoretically and experimentally determined, significant decays in flutter speed can suddenly occur with dramatic implications for the system structural integrity. Several passive methods used to address this problem include added structural stiffness, mass balancing, and speed restrictions¹. However, the attempt to enlarge the

operational range of any high flexible lifting structures and to enhance the aeroelastic response following these traditional methods result in significant weight penalties or in unavoidable reduction of nominal performances^{2,3}. All of these factors fully underline the necessity of the implementation of an active control capability enabling one to fulfill the two basic objectives of 1) enhanced subcritical aeroelastic response, in the sense of suppressing or even alleviating the severity of the wing oscillations in the shortest possible time, and 2) expanded flight envelope by suppressing flutter instability, thereby contributing to a significant increase in the allowable operational speed⁴. In this respect both supercritical and subcritical nonlinear

response in the proximity of the flutter boundary can be controlled with beneficial results.

The interest in the development and implementation of active control technology was prompted by the new and sometimes contradictory requirements imposed on the design of the new generation of the flight vehicle that mandated increasing structural flexibilities; high maneuverability; and, at the same time, the ability to operate safely in severe environmental conditions. Recently, a new $\mathcal{L}_1$ adaptive control theory has been developed for the control of uncertain non-autonomous nonlinear systems^{5,6}. The controller is based on a state predictor similar to indirect adaptive systems and the control input is obtained by a low pass filtering of the estimated control signal. This architecture provides several advantages over the traditional adaptive systems. In particular, the $\mathcal{L}_1$ adaptive controller guarantee fast parameter adaptation with a quantifiable performance bounds. This design approach has been already applied for the wing rock control⁷ of high speed vehicles, missile control⁸, and in other aerospace vehicles control operations⁹.

The application of $\mathcal{L}_1$ adaptive theory to aeroelasticity is in his infancy and investigations of the performances for several flight conditions are of great interest. As such, the development of an $\mathcal{L}_1$ adaptive flutter controller for the prototypical plunging and pitching 2D aeroelastic system and the results comparison with the existing nonlinear adaptive control¹⁰ are a starting point for more complex developments. This is the typical strategy adopted in control algorithm development, starting with the verification and validation of the strategy prior to any practical experimentation in wind tunnel or field testing campaigns. The design of the implemented controller is based on the $\mathcal{L}_1$ adaptive control theory¹¹. Whereas the comparative adaptive controller is based on a bank of filter able to estimate the immeasurable state variables. Then these filter variables are used to design a flap deflection control input in tandem with a gradient-based estimation scheme via the use of a Lyapunov function. Back-stepping is used to provide an extension to include the effect of controller dynamics. The two different type of controller were tested with the same aeroelastic model at the same condition to provide valuable results.

The type of aeroelastic model selected for the implementation of the control strategies is a two-DOF structurally nonlinear plunging and pitching lifting surface in a quasi-steady flow, which has been traditionally used for the theoretical as well as experimental analysis of flutter and post-flutter dynamics. The model has pitch polynomial type structural nonlinearities and uses a single moving surface for the purpose of control. It is assumed that all of the system parameters, except the sign of a single control input coefficient, are unknown. Whereas for the comparative adaptive control law¹⁰ the structures of both the aeroelastic model and the pitch spring constant nonlinearity must be

known. It was assumed a quasi-steady linear aerodynamic, a relatively acceptable assumptions for the purpose of comparison; needless to say, it is possible to extend this approach to account for linear/nonlinear unsteady aerodynamic models more suitable for reduced frequencies sufficiently large, $k = \omega b/U > 0.04$, where ω is the oscillatory frequency, b is the semi-chord, and U is the flow speed, and in the presence of dynamic stall and flow separation. Below 0.04, a quasi-steady approximation is usually sufficient to predict accurate loads on thin airfoils. However, it is worth mentioning, although the mechanism of flutter is usually correctly identified, a quasi-steady approximation might not always provide the correct flutter speed.

The proposed aeroelastic model exhibits a supercritical Hopf-bifurcation behavior, that is at free-stream velocity exceeding the critical flutter value, a stable Limit Cycle Oscillations (LCO) occurs. The $\mathcal{L}_1$ adaptive control was derived assuming only the pitch angle and its derivative available for measurements. As such, in the closed-loop system, both the pitch angle and plunge displacement trajectories are regulated. Unlike the traditional adaptive systems, the designed system has good robustness properties, and quantifiable performance bounds on the system output variable path and on the control input by the choice of adaptation and feedback gains. The rest of the paper is organized as follows. The second section, titled "Two-Dimensional Wing: Structural Model", introduces the system dynamics mathematical model. The third section describes the control objective. The fourth and fifth sections, titled respectively "Adaptive Back-Stepping Controller" and " $\mathcal{L}_1$ Adaptive Controller", provide a detailed description of the architecture and the design of the implemented and compared controllers. In "Simulation Results" section the comparative performance are obtained and evaluated. Finally, concluding remarks and future outlooks are presented in the closing section.

TWO-DIMENSIONAL WING: STRUCTURAL MODEL

Figure 1 shows a schematic for a plunging-pitching typical wing-flap section that is considered in the present analysis. This model has been widely used in aeroelastic analysis^{12, 13, 14, 15, 16, 17, 18, 19, 20, 21} and function as a benchmark model. The plunging (positive downward) and pitching (measured from the horizontal at the elastic axis of the airfoil, positive nose up) displacements are restrained by a pair of springs attached to the elastic axis (EA) of the airfoil with spring constants k_h and $k_a(\alpha)$, respectively. Here, $k_a(\alpha)$ denotes a continuous, linear parameterizable nonlinearity, that is, the aeroelastic system has a continuous nonlinear restoring moment in the pitch degree of freedom. Such continuous nonlinear models for stiffness result from a thin wing or propeller being subjected to large torsional amplitudes^{1,22}. Similar models^{12,15,16,23} have been

examined and provide a basis for comparison. The aeroelastic system permits two DOF motion, whereas an aerodynamically unbalanced control surface with flap displacement β (measured from the axis created by the airfoil at the control flap hinge, positive flap down) is attached to the trailing edge. In addition to controlling the aerodynamic flow and providing increased maneuverability, the flap is used here to suppress aeroelastic instabilities.

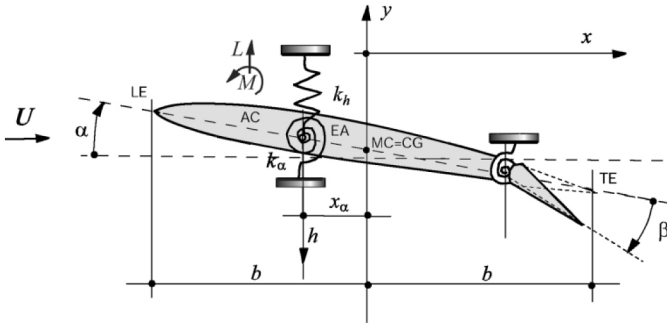


Figure 1. Two-dimensional wing section aeroelastic model

The governing equations of motion for the aeroelastic system under consideration are given by^{12,13}.

$$\begin{bmatrix} m & mx_{\alpha}b \\ mx_{\alpha}b & I_{\alpha} \end{bmatrix} \begin{bmatrix} \ddot{h} \\ \ddot{\alpha} \end{bmatrix} + \begin{bmatrix} c_h & 0 \\ 0 & c_{\alpha} \end{bmatrix} \begin{bmatrix} \dot{h} \\ \dot{\alpha} \end{bmatrix} + \begin{bmatrix} k_h & 0 \\ 0 & k_{\alpha}(\alpha) \end{bmatrix} \begin{bmatrix} h \\ \alpha \end{bmatrix} = \begin{bmatrix} -L \\ M \end{bmatrix} \quad (1)$$

where the lift L and aerodynamic moment M can be modeled as^{10,23}

$$\begin{aligned} L &= \rho U^2 b c_{l\alpha} \left[\alpha + \frac{\dot{h}}{U} + \left(\frac{1}{2} - a \right) b \left(\frac{\dot{\alpha}}{U} \right) \right] + \rho U^2 b c_{l\beta} \beta \\ M &= \rho U^2 b^2 c_{m\alpha} \left[\alpha + \frac{\dot{h}}{U} + \left(\frac{1}{2} - a \right) b \left(\frac{\dot{\alpha}}{U} \right) \right] + \rho U^2 b^2 c_{m\beta} \beta \end{aligned} \quad (2)$$

where a is the non-dimensionalized distance from the midchord to the elastic axis, so that: $x_{\alpha} = a * b$.

Following the development of Ref. 13, one can transform the governing equations of motion of Eq. (1) into the following equivalent state-space form as follows:

$$\dot{z} = f(z) + g(z)\beta, \quad y = z_2 \quad (3)$$

where $z(t) = [z_1 \ z_2 \ z_3 \ z_4]^T \triangleq [h \ \alpha \ \dot{h} \ \dot{\alpha}]^T$ is a vector of system states, $\beta(t) \in R^1$ is a flap deflection control input, $y(t) \in R^1$ denotes the designated output, and $f(z)$ and $g(z) \in R^1$ assume the following form:

$$\begin{aligned} f(z) &= \begin{bmatrix} z_3 \\ z_4 \\ -k_1 z_1 - [k_2 U^2 + p(z_2)] z_2 - c_1 z_3 - c_2 z_4 \\ -k_3 z_1 - [k_4 U^2 + p(z_2)] z_2 - c_2 z_3 - c_4 z_4 \end{bmatrix} \\ g(z) &= \begin{bmatrix} 0 \\ 0 \\ g_3 U^2 \\ g_4 U^2 \end{bmatrix}, \quad g_4 \neq 0 \end{aligned} \quad (4)$$

where $p(z_2)$ and $q(z_2) \in R^1$ are continuous, linear parameterizable nonlinearities in the output variable resulting from the nonlinear pitch spring constant $k_{\alpha}(\alpha)$. The auxiliary constants k_i and $c_i \ \forall i = 1, \dots, 4$, as well as g_3 and g_4 , are explicitly defined in Ref. 10. Motivated by the desire to rewrite Eq. (3) in a form that is amenable to output feedback control design, Kalman's observability test is applied to the pair $(\bar{A}, C)$, where $\bar{A} \in R^{4 \times 4}$ and $C \in R^{1 \times 4}$ are explicitly defined as

$$\bar{A} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -k_4 U^2 & -c_4 & -k_3 & -c_3 \\ 0 & 0 & 0 & 1 \\ -k_2 U^2 & -c_2 & -k_1 & -c_1 \end{bmatrix}, \quad C = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (5)$$

A sufficient condition for the system (3) to be observable from the pitch angle output $\alpha(t)$ is given as

$$d_{obs} = k_3^2 - k_3 c_3 c_1 + c_3^2 k_1 \neq 0$$

which is easily satisfied by the nominal model parameters of the 2-DOF aeroelastic system presented here. After a series of coordinate transformations, the governing equations for the aeroelastic model can be expressed in the following convenient state-space form:

$$\dot{x} = Ax + \Phi(y) + B\bar{\beta}, \quad y = C^T x = [1 \ 0 \ 0 \ 0]x \quad (6)$$

Herein, $\bar{\beta} = U^2 \beta$ is an auxiliary control input, $x \in R^4$ is a new vector of system states, and $\bar{A} \in R^{4 \times 4}$ and $B \in R^4$ are explicitly defined as

$$\bar{A} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix}, \quad C = \begin{bmatrix} 0 \\ \theta_2 \\ \theta_3 \\ \theta_4 \end{bmatrix} \quad (7)$$

Where $\theta_i \ \forall i = 2, 3, 4$ are constants, explicitly defined in Ref. 10. In Eq.(6), $\Phi(y) \in R^4$ is a smooth vector field that can be linearly parameterized as follows: