Controlling Chaotic Motions of a Nonlinear Aeroelastic System Using Adaptive Time Delay Feedback Control

Robert Bruce Alstrom[1], Goodarz Ahmadi[2], Erik Bollt[3], Pier Marzocca[4]

Clarkson University, Potsdam, New York 13699-5725

ABSTRACT

In this paper the application of an adaptive reference free time delay-feedback controller to a chaotic nonlinear aeroelastic system will be examined. Two degree-of-freedom aeroelastic systems are subjected to steady and unsteady aerodynamic loads will be considered. The use and effectiveness of plunging and pitching displacements and their rates as feedback signals for suppressing the chaotic dynamics of the wing will be evaluated. In addition to these simulations, a study of the controller parameters will be presented for each of the above mentioned feedback signals.

INTRODUCTION

Aeroelasticity has been and continues to be an important consideration in the design of primary flight structures. In particular, dynamic aeroelastic effects such as flutter, limit cycle oscillations and in some instances chaotic motion can place severe operational constraints on flight vehicle performance. To that end, Dimitriadis and Cooper [1] addressed the topic of limit cycle control via limit cycle switching. Limit cycle switching refers to the forcing of an aeroelastic system to jump from one limit cycle to another by applying a control excitation signal. Limit cycle switching suggests that it is possible to force an aeroelastic system to a limit cycle of smaller amplitude or even a decaying response resulting in the control of the limit cycle or full suppression. Dimitriadis and Cooper designed such a controller by feeding back the damping term of the trailing edge flap. It was noted in this study that when the aeroelastic system assumed the new limit cycle, the amplitude of the feedback signal decreased significantly. In 2001, Ramesh and Narayanan [2] successfully demonstrated that they could control the chaotic motion of an aeroelastic system using self controlling delayed feedback discussed by Pyragas in the physics literature [3]. Specifically, it has been demonstrated that a chaotic attractor has embedded within it an infinite number of unstable periodic orbits. Pyragas applies continuous time delayed feedback in which a system parameter is perturbed in proportion to the difference between the delayed output signal and the current signal of the dynamical system as shown in Figure 1.

[1] Graduate Student, Department of Mechanical and Aeronautical Engineering, AIAA Senior Member
[2] Professor, Department of Mechanical and Aeronautical Engineering
[3] Professor, Department of Mathematics and Computer Science
[4] Associate Professor, Department of Mechanical and Aeronautical Engineering, AIAA Senior Member

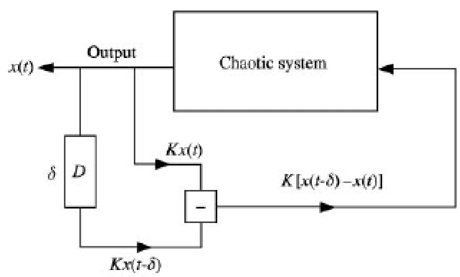

Figure 1. Schematic of delayed-feedback control system [3].

In this current paper, aeroelastic models (Figure 2) presented by Shahrzad and Mahzoon [4] and Rubillo et al [5] will be used. The steady nonlinear aeroelastic governing equations are given as follows:

$$\mu\ddot{h} + \mu\chi_\alpha \ddot{\alpha} + \zeta_h \dot{h} + \mu\left(\frac{\omega_h}{\omega_\alpha}\right)^2 h = -\frac{Q_h}{\pi\rho b^3\omega_\alpha^2} \quad [1]$$

$$\mu\chi_\alpha\ddot{h} + \mu r_\alpha^2\ddot{\alpha} + \zeta_\alpha \dot{\alpha} + \mu r_\alpha^2\alpha + \frac{\varepsilon}{\pi\rho b^4\omega_\alpha^2}\alpha^3 = \frac{Q_\alpha}{\pi\rho b^4\omega_\alpha^2} \quad [2]$$

where h and α are the plunge and pitching angle displacements and Q_h and Q_α are the aerodynamic lift and moment forces respectively. The following parameters were used:

$\mu = 12.8, b = 0.118, \zeta = 0.2, \omega_h = 34.6, \omega_\alpha = 88, r_\alpha^2 = 0.3, \varepsilon = 20$ and $\chi_\alpha = 0.15$.

The steady version of this model was observed by Rubillo et al [6] to exhibit flutter at 17.19 m/s and chaotic behavior at 40 m/s (See Figures 3 and 4).

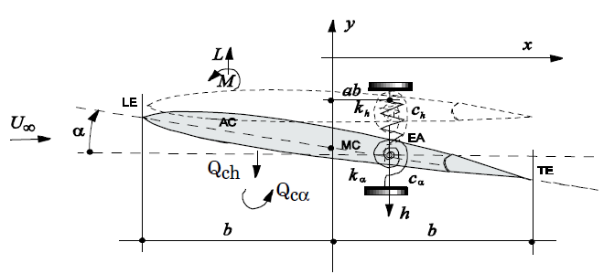

Figure 2. Two degrees of freedom aeroelastic model [4].

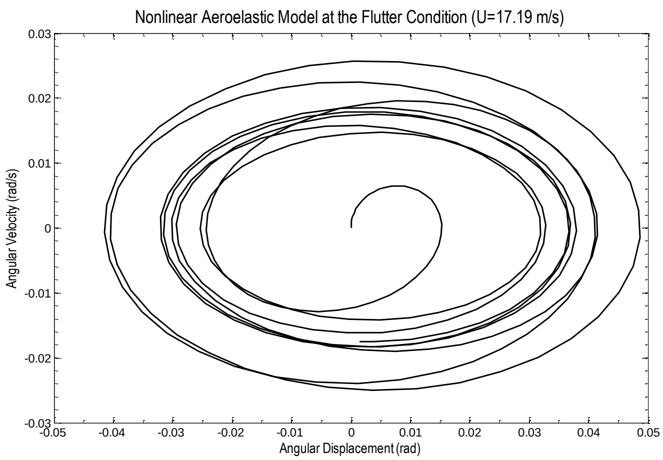

Figure 3. Aeroelastic Model at Flutter, U=17.19 m/s.

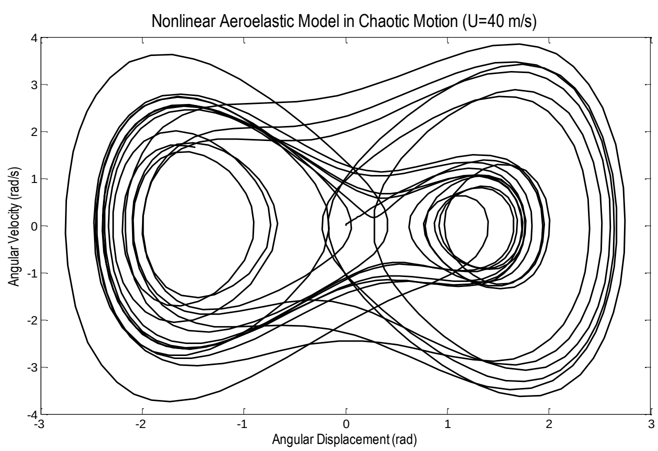

Figure 4. Aeroelastic Model in chaotic motion, U=40 m/s.

In the final version of the paper both a steady and an unsteady formulation will be implemented. Within these formulations, control strategies will be employed. The control strategy presented in Ref [3] and applied to various well known nonlinear systems will be revisited and adopted for the proposed aeroelastic systems. By applying a reference free adaptive time delay feedback controller the authors intend to explore the performance of the proposed control strategy to drive an aeroelastic system from a chaotic state to a stable state. Figure 5 shows the schematic of the original concept presented by Pyragas [6].

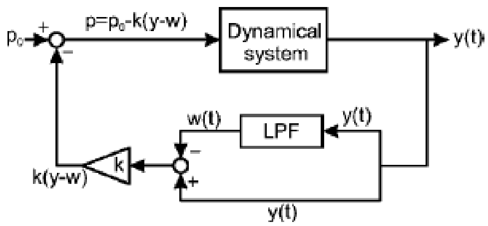

Figure 5. Adaptive control with low pass filter [6].

The control scheme shown here is based on an unstable low pass filter that is reference free thus it does not require prior knowledge of an unstable fixed point in the phase space. The application of time delay provides the capability to make steady unstable periodic orbits that may be exhibited by the aeroelastic system. The time delay is applied to the output of the low pass filter, that is:

$$u(t) = K[y(t) - w(t - \delta)] \quad [3]$$

where u(t) is the external control signal and δ is the time delay. The low pass filter is characterized by a first order differential equation given by:

$$\dot{w}(t) = \omega^c\big(y(t) - w(t)\big) \quad [4]$$

The filter parameter ω^c is the cutoff frequency. It has been shown that small cutoff frequencies stabilize more unsteady states. In this study, the application of all four states will be investigated as feedback signals, i.e. plunging displacement and rate and pitch angle and rate will be evaluated.

Preliminary Results

Preliminary closed-loop aeroelastic simulations are presented next. For these simulations, the angular displacement is selected as the feedback signal. The controller parameters are K=1.05, ω^c=0.05 and δ=25. Figure 6 shows that the controller stabilizes the flutter mode at 17.19 m/s within 150 seconds after the simulation was released from initial conditions. Note that the amplitude of u (t) decreases as the pitch and plunge oscillations subside.

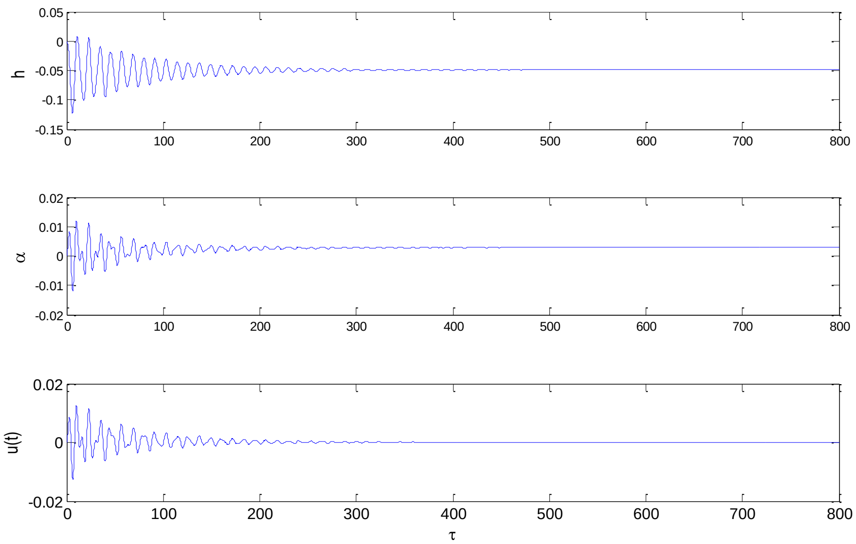

Figure 6. Response to closed loop control at Uf=17.19 m/s

Figure 7 shows that through the use of the proposed control strategy, the chaotic motion is confined to a stable orbit denoted by the trajectory identified by the solid red line; note that the right lobe has decreased significantly in amplitude. The controller parameters for this simulation were estimated based on the observed dynamics of several simulation runs. In the final version of the paper, a parametric study of the three controller parameters will be conducted and examined for their effect on stabilizing the aeroelastic system for each choice of feedback signal. In addition, the concept of limit cycle switching introduced earlier will be investigated to determine if it is possible to force the aeroelastic system to switch from chaotic motion to a stable period-one limit cycle oscillation or possibly suppression.

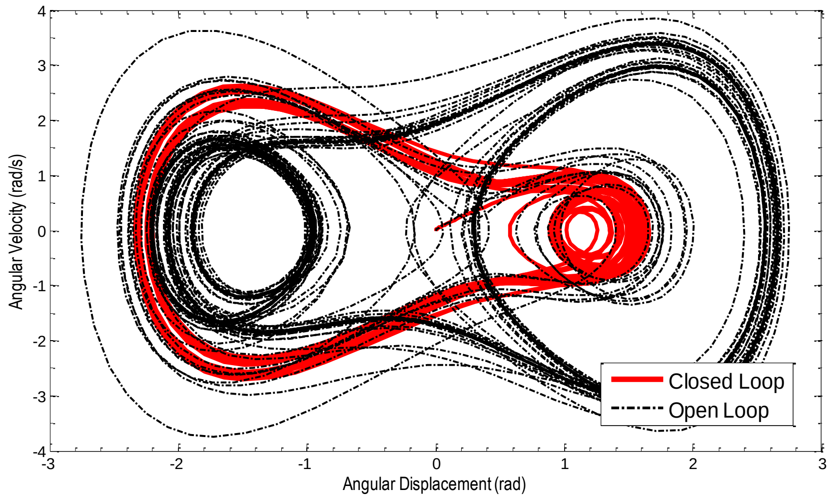

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Figure 7. Comparison of open and closed-loop aeroelastic behaviors.

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