The Effect of Electro-Hydraulic and Electro-Hydrostatic Actuators Dynamics on the Adaptive Control of Chaotic Motions of a Nonlinear Aeroservoelastic (ASE) System

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ABSTRACT

INTRODUCTION

Aerodynamic flutter refers to a subject that has evolved since the beginning of manned flight. Aeroelasticity continues to occupy a prime role in the current design of advanced aircraft, missiles and launch vehicles. With the advent of modern flight control systems, the disciplines of aeroelasticity and structural dynamics are linked together by the interaction between the aeronautical structure and the flight control system and associated sensors; this is known as aeroservoelasticity (ASE). Aeroservoelasticty exists primarily because of the excitation of the flight vehicle's structural modes can cause both oscillatory aerodynamic loads and flight control system demands that result from the airframe mounted motion sensors; the aeroservoelastic interaction comes from these secondary responses which induce further excitation of structural modes [Taylor and Pratt]. It is common practice to apply notch and low pass filters to the flight control system in order to meet the stability and gain margins required to clear an aircraft for flight. But in doing so one can incur undesirable phase lags at the rigid body frequencies. The secondary oscillatory dynamics mentioned previous, often present as limit cycle oscillations (LCO). There is a distinction to be made between the LCOs caused by ASE interaction and those caused principally by the aero-structure itself. Hence it is instructive to understand the mechanism by which limit cycles and chaotic motions are created. A limit cycle is a standing periodic oscillation that is characterized in the phase plane as a single loop; in some instances a multi-frequency limit cycle may appear as in the case of a chaotic system that has been transformed by an appropriate control force. For a stable limit cycle, the rate of energy input from the freestream is equal to the energy dissipation rate. A limit cycle that is unstable under the

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following physical conditions; when the system continuously receives more energy than it is able to dissipate, the limit cycle will grow in amplitude. Conversely, if energy is extracted from the system, then the oscillation will decay. It is this mechanism that makes it possible to force an aeroelastic system to switch limit cycles. We will revisit the notion of an unstable limit cycle and limit cycle switching later. For now we will introduce examples of limit cycle switching and suppression.

The first such example as pointed out by Dimitriadias and Cooper [1] was work performed by Holden et al [2]. Specifically, during a series of wind tunnel tests on a flutter model of a tail plane, Holden and his colleagues noticed that applying a certain excitation signal caused an LCO; the re-application of the same signal a short time later produced a limit cycle of larger amplitude. The manipulation of limit cycles has a lot to do with the energy state of the system. There are devices which have the capability to make instantaneous changes of its mass, stiffness or damping; such devices are termed state switchable dynamical systems. For example if a switchable stiffness element is build into a vibration absorber, the change in stiffness causes a change in the resonant frequencies of the system and thus 'retuning' the system. One can design a switching rule-control law that extracts energy from the system [3, 4]. Lee et al [5] demonstrated that one can use continuously varying stiffness and damping elements (or nonlinear energy sinks –NES) coupled to a van der Pol oscillator. By adjusting the parameters of the NES indicated in Figure 1, suppression of LCOs can be achieved.

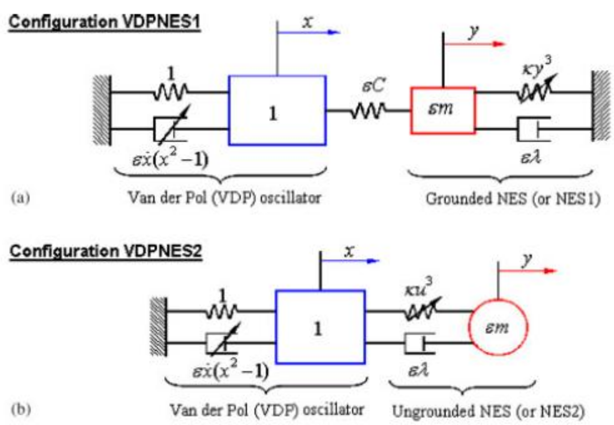


Figure 1. System configuration with: (a) grounded NES; (b) ungrounded NES [5]

Now let's revisit the discussion on unstable limit cycles also referred to as unstable periodic orbits (UPOs); for a system with sufficient complexity (i.e. multiple degrees of freedom, number and type of nonlinearities), a significant number of limit cycles can exist in its phase plane. As such the key is to force a system into a stable limit cycle knowing the location of the unstable limit cycles that surround it. A very similar argument was made by Pyragas [6]. Specifically; the stabilization of unstable periodic orbits of a chaotic system is achieved by applying a combined feedback with the use of a specially designed external oscillator or by a delayed self controlling (Figure 2) feedback force without the use of an external force. Both of these methods do not require any prior analytical knowledge of the system. These methods make use of the fact that there are an infinite number of unstable periodic orbits contained in a chaotic attractor. The delayed-self controlling method was successfully demonstrated for an aeroelastic system by Ramesh et al [7].

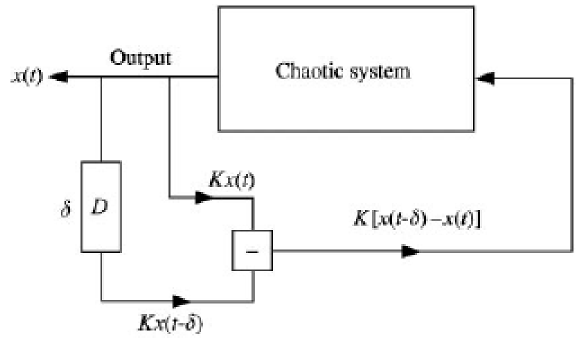


Figure 2. Schematic of delayed-feedback control system [6].

However suppression is a necessary requirement for airworthiness and certification. To achieve full suppression of the said chaotic system, it is the objective of this paper to show that the application of a simple adaptive controller which is based on a low pass filter is able to stabilize a highly dynamic aeroelastic system. In addition to the LCO suppression study, we will also address the effect of time delay on an adaptive flutter suppression algorithm. Short time delays in control systems are unavoidable especially when digital controller are used. Other sources of time delay are actuators, sensors, mechanical linkages, and filters. [8]. Time delays can significantly impact a closed-loop system if the control demand induces large control forces or if the controller is unable to handle high frequencies. Time delays when appropriately applied can constrain an aeroelastic system to a limit cycle as demonstrated by Ramesh et al [7]. The application of or occurrence of a time delay event at the wrong time can degrade the control system performance [9]. It is important for aerospace engineers to understand the effect of inherent time delays so that they can be mitigated or designed out early in the flight dynamics work up on a major aircraft program. The effect of time delays have been studied for a simple aeroelastic system in [8, 9]. In particular, the effect on the flutter boundary has been covered in the literature with full-state feedback control; see e.g. [12, 13, and 14]. The present paper only addresses the lifting surface post-flutter behavior and its control through the adaptive reference-free feedback controller.

ADAPTIVE CONTROLLER

Controlling chaotic behavior mainly deals with the stabilization of unstable periodic orbits. The stabilization of a fixed point by classical methods requires knowledge of the location in the phase space. For many complex systems, the locations of the fixed points are not known a priori; as such, adaptive control techniques that are capable of locating unknown steady states are desirable. A simple adaptive controller for stabilizing unknown steady states can be designed using ordinary differential equations (ODEs). One such controller utilizes a first order ODE that represents a low pass filter (LPF). The filtered DC output of the filter estimates the location of the fixed point, such that the difference between the actual and the filtered signal can be used as a control signal. This control signal is then scaled by a proportional gain. The structure of the system is represented in Figure 5.

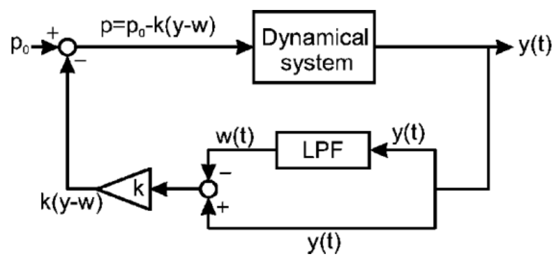


Figure 3. Block diagram of adaptive controller. LPF denotes low pass filter [11]

In general mathematical terms, when considering an autonomous dynamical system as the one in Figure 3, a description by a set of ordinary differential equations can be cast as:

(5)

where the vector defines the dynamical variables and *p* is the total control force. The scalar variable is a function of the systems states; for the aeroelastic system, *y(τ)* could be anyone of the four states i.e. pitch, plunge, or any of their rates. Suppose that , that is the system has an unstable fixed point at *x** that satisfies . If the steady state value $y^*=g(x^*)$ corresponding to the fixed point were known, one could try to stabilize it using classical proportional feedback control.

(6)

Suppose now, that the reference value y^* is unknown. The objective will be to construct a reference-free feedback perturbation that automatically locates and stabilizes the fixed point.

When the controller locates the fixed point, the control input should vanish i.e. no control power should be dissipated in the closed-loop condition. The controller that satisfies the requirements can be constructed from an ODE that represents a low pass filter given by the following equation:

(7)

Here, *w* is a controller variable and the parameter, represents the cut-off frequency of the filter. The output of the filter provides an averaged input variable *y (τ)*. If *y(τ)* oscillates about the steady state value of y^* one can expect that the output variable *w(τ)* will converge to this value. As result the reference value *y** can be replaced with the output variable of the filter; that is the control force can now be expressed in the following way:

(8)

The complete control-loop is in fact a high-pass filter, since the second term in Eq. (8) is obtained from the difference of the actual output signal and filtered by the LPF. The control signal is proportional to the derivative of the controller variable *w* i.e.

— (9)

As , from Eq. (5), it follows that ; for large , the control signal becomes proportional to the derivative of the output . When this happens, the controller behaves as a simple derivative controller. In order to implement the time delay parameter, the output of the low pass filter, *w (t)*, is shifted by δ such that Eq. (8) can written in the following manner:

(10)

For our numerical study, is set to zero so that the system is reference free and .

LIMIT CYCLE CONTROL AND SUPPRESSION RESULTS

The adaptive reference free controller was applied to a two degree of freedom aeroelastic model shown in Figure 4. Numerical simulations are performed using the aeroelastic governing equations based on parameters provided in [9] and adapted to give the following:

(11)

(12)

The given system equations have the flutter speed is . Figure 5 shows the airfoil in the open loop post flutter condition at Q=16.8.

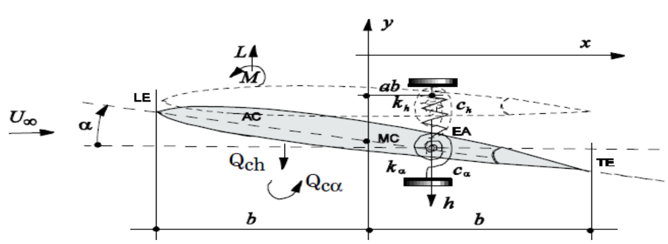


Figure 4. 2DOF Aeroelastic Model

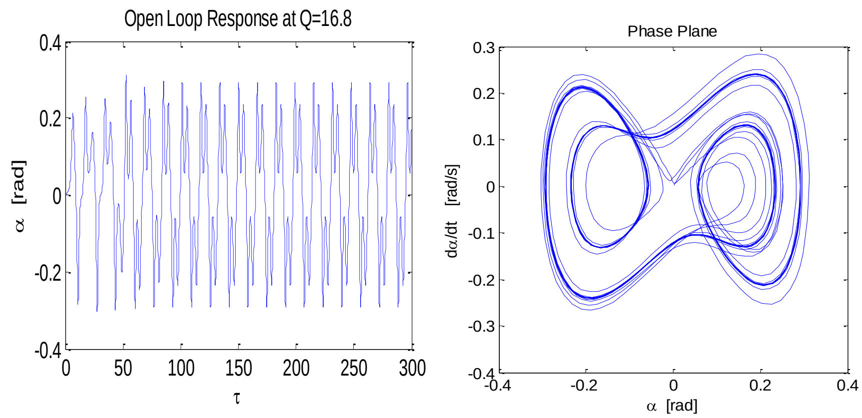


Figure 5. Post flutter open loop regime

In the study, results on limit cycle control are presented [Alstrom et al]. The results consisted of a parametric analysis and time history plots that pertain to the parametric system. Limit cycle control can be thought of as the act of extracting energy from the system such that the amplitude of the limit cycle decreases. For the aeroelastic system under investigation it is the control of its dynamics in the post flutter regime that are of interest. Thus limit cycle control in this application means transforming the chaotic motion of the wing into a limit cycle. Specifically, a parametric analysis is used to gain insight into how the controller parameters affect the closed-loop system as well as provide guidance on which state variable to employ as a feedback signal. The feedback gain *k*, is evaluated at three filter cut-off frequencies; 0.001 rad/s, 0.01 rad/s and 0.1 rad/s. In addition to the LCO control and suppression results, the effect of time delay was also investigated. We will present some results from that work. It was found that the adaptive reference free controller was able to transition the aeroelastic system a chaotic state to a limit cycle oscillation and fully suppress the chaotic motion as evidenced by Figures 6 and 7. Further under closed loop control, regions of instability are present for specific values of time delay (See Figure 8)

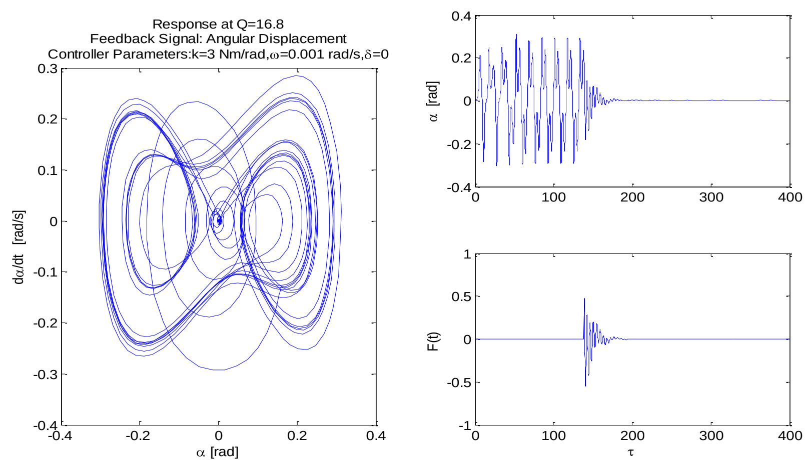


Figure 6

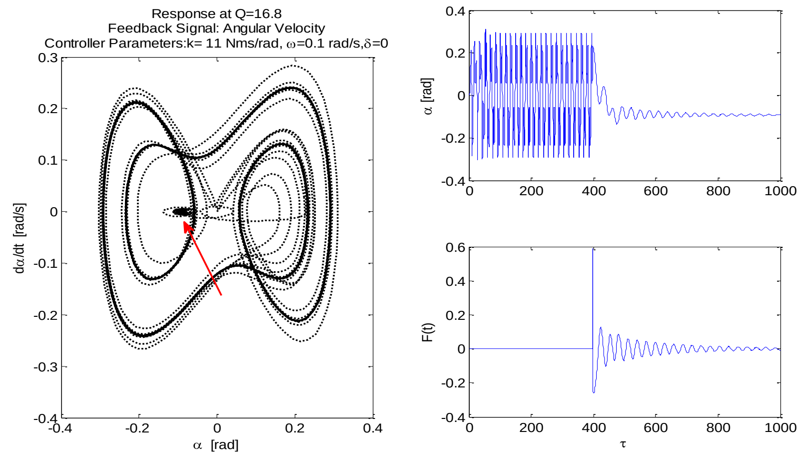


Figure 7.

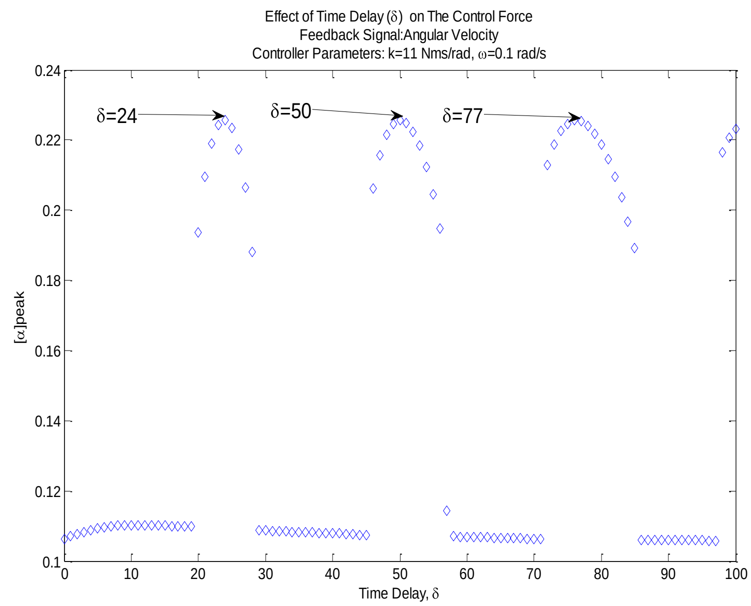


Figure 8

FUTURE WORK

The majority of closed loop aeroservoelastic work does not always include the actuator dynamics. If the actuator dynamics are presented, it is observed that the nonlinearity is either in the aero-structure or the actuator but tend not to be cascaded or in series under closed loop control [DC2000]. The other combination seen it the literature is the trailing edge flap has a stiffness that can be transformed into a nonlinearity and no structural nonlinearity in the 2D wing model. Further, the closed loop controllers developed for this type of system tend also to consider one nonlinearity at a time (i.e. either rate limiting or saturation) [Demenkov]; real flight control actuators have multiple nonlinearities [Taylor and Pratt]. The inclusion of the actuator dynamics is more common place in flight control system development work. The actuator dynamics are often linear transfer function relationships. However, in order to get a proper understanding of the stability and gain margins one needs to consider the actuator nonlinearities. In Figures [a and b] we see that the control signal is 'perfect' in the sense that the actuator dynamics are ideal i.e. unity gain; Will the adaptive control signal still be able to suppress the chaotic motion with the actuator dynamics included? The aim of this follow on work is to investigate the effects of simulated nonlinear actuator dynamics on the designed control signal's capability to provide suppression to the aeroelastic system with and without time-delay. To facilitate this evaluation, a 2D nonlinear wing with a trailing edge flap from the Texas A& M Aeroelasticity Group will be used [Ko et al] (Figure 9)

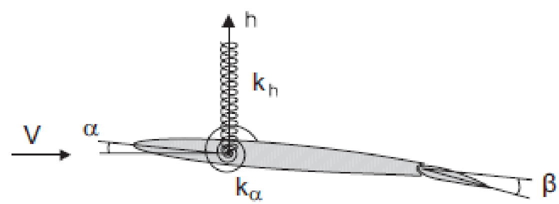


Figure 9 Flap actuated aeroelastic system []

This model allows for coupling of the actuation system in series with the aeroelastic plant as the flap displacement input to the system as given by Eqn. 13

(13)

Nonlinear Actuation System Modeling

For the purposes of this study, we will examine the effect of 2 types of actuators; they are the electrodydraulic actuator and the electro-hydrostatic actuator. Electrohydraulic actuators (EHA) and electromechanical actuators (EMA) are typically used in aircraft flight control and stability augmentation systems (SAS) [Taylor and Pratt + NASA TN D-6928]. A traditional aircraft servo-hydraulic system has the components shown in Figure X.xx. The EHA (non-hydrostatic) is composed of four main components, the actuator control or command system, then main valve actuation, the main valve and the ram.

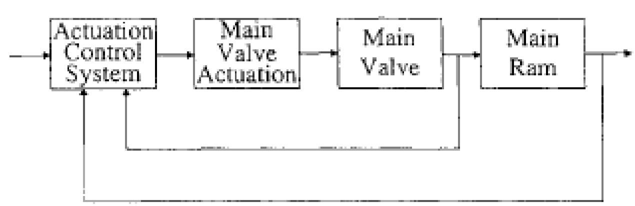


Figure 10. Typical Electrohydraulic Actuator []

The electro-hydrostatic actuator (Figure 11) differs from the hydraulic version in that it does not require a central hydraulic power supply which eliminates the need for plumbing. Instead the EHA (hydrostatic) uses electrical cables. Specifically, the hydrostatic actuator is a Power-By-Wire (PBW) actuator that utilizes the hydraulic pump to transfer the rotational motion of the electrical motor to the actuator output. The EHA (hydrostatic) is based principally on closed circuit hydrostatic transmission; as a result the need for oil reservoirs and electro-hydraulic servo-valves are eliminated. The EHA (hydrostatic) to be used in this work is a fixed pump displacement with variable motor speed or FPVM. A version of the electro-hydrostatic actuator designed by Moog Inc is currently being flown on the F-35 Lightning II (Joint Strike Fighter).

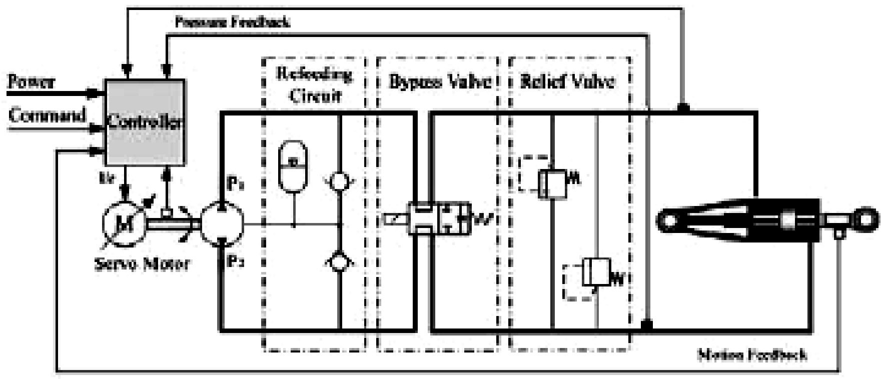
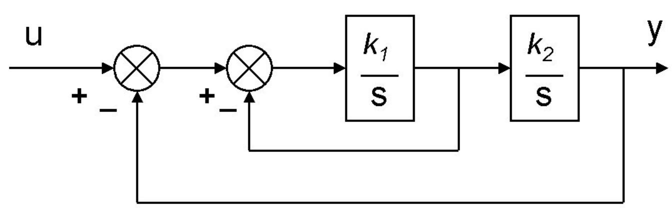


Figure 11. Electro-Hydrostatic Actuator []

Due to the complexity of the nonlinear models for both types of EHA, we will begin the analysis with a linearized second order model of a generic electrohydraulic actuator (Figure 12) as is given by Fielding and Flux [ ]



$$\omega_n = \sqrt{k_1 k_2} \qquad \zeta = 0.5\sqrt{k_1/k_2}$$

Figure 12. Second order linearized actuator [ ]

In Figure 12, we see that there are two typical actuator nonlinearities, acceleration limit and rate limiting. The model shown above contain some simple equations that allow for a parametric analysis of the effect of inner and outer loop saturation on the capability of the control signal to suppress the chaotic motion. It will also be possible to predict the frequency at which rate or acceleration saturation will occur; by completing such an analysis we can effectively design the actuators frequency response to accommodate the control signal [Taylor and Pratt]. These properties are of importance because the actuator authority and bandwidth can become severely reduced [Stirling] in the presence of large amplitude signals. Following this analysis, a full nonlinear simulation of the electro-hydrostatic actuator will be coupled to the flap actuated aeroelastic model. The electro-hydrostatic model contains a friction model can be considered a dead-zone nonlinearity, also typically found in flight control system actuators.