CONSTRAINED MULTI-OBJECTIVE OPTIMISATION OF A CONTROLLER FOR A HIGHLY NONLINEAR AEROELASTIC STRUCTURE—TESTBED DESIGN

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ABSTRACT

The need for weight-optimised aerospace structures results in flexible structures with highly nonlinear behaviour. Their control presents challenges that require control theory be developed in order to enable the trend toward lighter structures to continue. Two classes of problem of particular interest in control are systems with a high degree of nonlinearity inherent in the structure and those with nonlinear and noncontinuous external forces. These are represented respectively by space structures and those subject to aeroelastic effects.

The problem of control of highly flexible space structures have previously been considered by the author (Drack, Zadeh, Wharington, Herszberg and Wood, 1999; Zadeh, 2002). Optimal control of a two dimensional aeroelastic (wing) structure with three degrees of freedom is considered. Due to publication space limitation, results are presented in two papers; this and a follow-up paper (Zadeh, 2005).

INTRODUCTION

Weight is of primary concern in aircraft design, affecting all performance indicators, with the extensive use of composite materials being testimony to this. In special application aircraft, such as those intended to operate at very high altitude with very low wing loadings, the wing becomes a high aspect ratio, lightweight, flexible structure. The ability to produce a lighter structure that is immune to the potentially destructive effects of aeroelasticity is thus very desirable.

Although conventional control theory is reasonably well-established and mature, it is mainly limited to rather simple applications. Control of aeroelastic behaviour of aerospace structures pose various challenges which limit the usefulness of conventional control techniques.

The characteristics common to these class of applications are:

- there usually exist high number of hidden or unobservable states, making the use of state estimators difficult. These include aerodynamic states, and structural bending and torsional states.
- these systems are highly nonlinear, limiting the applicability of conventional state space techniques. For example, aerodynamic loads are nonlinear and sometimes even noncontinuous.
- these structures are difficult and very expensive to test.

Controllers needed in aerospace applications usually needs be optimal with respect to multidisciplinary criteria and a variety of potentially conflicting constraints, as well as being robust with respect to system parameter variations and uncertainties.

Fuzzy Logic Control (FLC) is considered as a non-conventional control stratagem for designing control systems that can cater for system nonlinearities and discontinuities (MathWorks Inc., 1994).

FLCs are usually designed by providing expert input to the controllers in the form of linguistic phrases (Wang, Mo and Chen, 1995; MathWorks Inc., 1994). Expert advice can thus be intuitively implemented, however, the resulting FLC is a nonlinear and potentially discontinuous transfer function that maps input(s) to output(s). Furthermore, this method of control design can also result in sub-optimal controller performance.

Conventional control techniques usually cannot be applied to design of FLCs, as they are, by their very nature, nonlinear. Therefore, FLC design methodologies require either hand-tuning or numerical optimisation in order to achieve superior or robust performance.

Such diverse performance requirements could mean that if such performance is showed to be satisfied on the test problems, there is some evidence that the methodology will be applicable to broader classes of problems.

The optimiser required for this task must be capable of handling many local minima, and be able to achieve a good result on current computing hardware in a reasonable period of time. Simulated annealing (Kirkpatrick, Gelatt Jnr. and Vecchi, 1983; Ingber, 1993) is used in this research in place of calculus based optimisation techniques in order to overcome the above difficulties.

This paper is organised into a number of sections. Aeroelastic instability is explained in the next section, followed by definition of the research problem. The aeroelastic testbed, and design of a nominal fuzzy logic controller are then covered. Simulation methodology and simulation results of the nominal controller are presented.

The nominal controller has been used as the basis for designing an optimised controller using a constrained, multi-criteria, stochastic optimisation scheme. Because of publication space limitations, the optimisation of the controller has been submitted as a separate, follow-on, publication (Zadeh, 2005).

CONTROL OF AEROELASTIC SYSTEMS

Aeroelastic phenomena occurs due to a combination of inertia, aerodynamics, and elastic forces (Figure 1). Aeroelasticity (and particularly aeroelastic instability) did not attain

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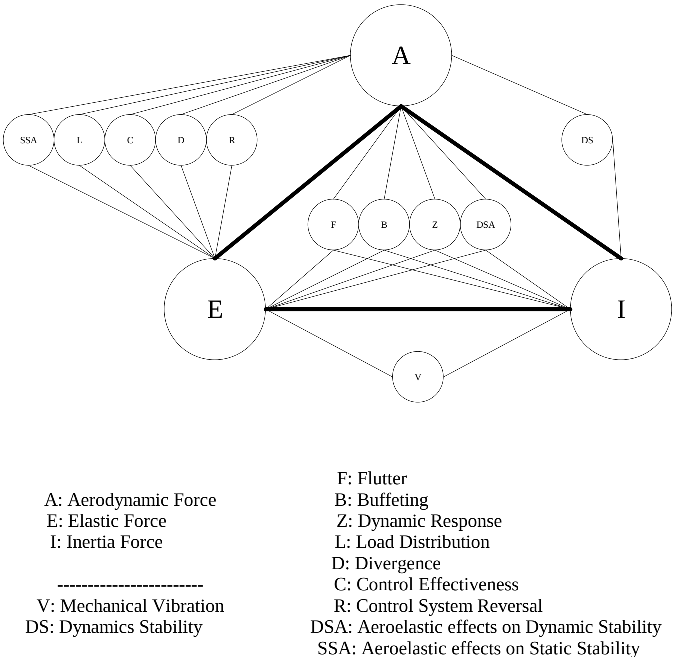

Fig. 1. Aeroelastic triangle of forces (Bisplinghoff et al., 1955)

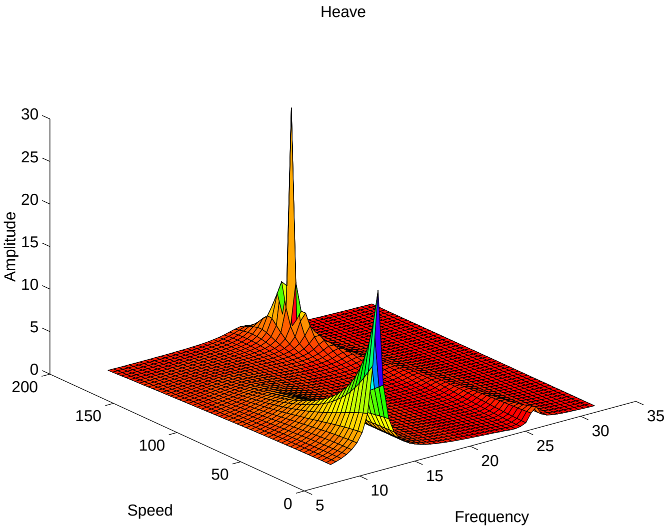

Fig. 2. Shift in Heave Resonance Amplitude of an Aeroelastic Structure (Wing) vs. Frequency of Excitation and Translational Speed

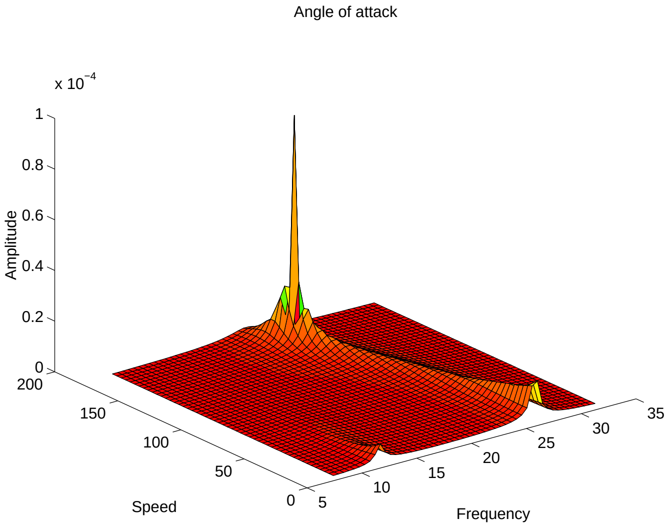

Fig. 3. Shift in Angle of Attack Resonance Amplitude of an Aeroelastic Structure (Wing) vs. Frequency of Excitation and Translational Speed

a prominent role until the early stages of World War II. Prior to that time, aeroplane speeds were relatively low and the load requirements placed on aircraft structures by design criteria produced structures sufficiently rigid to preclude most aeroelastic phenomena. As speed increased, however, with little or no increase in load requirements, and in the absence of rational stiffness criteria for design, aircraft designers encountered a wide variety of problems that are now classified as aeroelastic problems.

One of the interesting problems in aeroelasticity is the instability of a structure in wind. At zero airspeed, aerospace structures exhibit one or more natural frequencies. As can be seen in Figure 2, at zero speed, the testbed structure has two *heave* natural frequencies in the range displayed in the figure. Figure 3 shows the two *torsional* natural frequencies of the same structure.

As forward movement is commenced and speed is increased, aerodynamic forces start extracting energy from the system, thereby reducing amplitude of any induced vibration. This is true for both bending and torsional motions of the structure. Aerodynamic forces, for a given configuration, increase rapidly with velocity, while the elastic stiffness is independent of the velocity.

As speed reaches a certain threshold, however, the trend may be reversed and the structure may start extracting energy from the air stream. Natural frequency of the system, in both bending and torsion, start merging to the same frequency. This is clearly evident in Figures 2 and 3.

There may exist a critical speed at which the structure becomes unstable. At flutter speed, a small disturbance induces violent oscillations, characterised by the interaction of aerodynamic, elastic, and inertia forces. This phenomenon is usually referred to as dynamic aeroelastic instability. The special case of instability with zero frequency (in other words, destruction without oscillation) is called steady-state, or static aeroelastic instability.

At flutter speed the vibration is unstable; a small disturbance sets off a small vibration in the structure. Extracting energy from the air stream, amplitude of vibration is increased without bound, usually resulting in destruction or severe deformation of the structure. This is evident in Figures 2 and 3.

As on-board computational power is increasing and is also becoming more robust, it is only a matter of time before active control of aeroelastic instabilities becomes viable.

PROBLEM DEFINITION

In order to examine the design methodology of a robust, multi-objective, and stochastic optimal controller, a real-life wing structure was used as the basis for the simulation testbed. The structure was chosen to represent a class of aerospace structures that has traditionally been one of the most obscure and difficult problems to analytically analyse and control.

A model of the structure is developed for the purposes of high-fidelity simulation and evaluation. Structure modelling and controller design specifications are explained below.

A nominal fuzzy logic controller was designed and implemented following the procedure set out in (Zadeh, 2002). The universe of discourse of each input was covered using seven membership functions. Similarly seven membership functions were used for the output.

The nominal controller has been used as the basis for designing an optimised controller. Methodologies and simulation results of the optimised controller have been submitted as a follow-on publication (Zadeh, 2005).

AEROELASTIC TESTBED

A real-life wing structure is modelled with three structural degrees of freedom, namely heave, angle of attack (alpha), and aileron rotation (beta). There are also six additional states due to the unsteady aerodynamic system. These states however, are hidden from the controller. To overcome the effect of the hidden states on the controller, geometry and speed is kept constant during the simulation eliminating the possibility of perceptual aliasing.

Modelling

The formulation of flutter equations and their solution can be a very tedious and time consuming task. It usually results in an eigenvalue problem which can be quite complex, or even practically impossible to solve by analytical methods.

In practise one of several indirect methods is often used to compute the flutter velocity. One of these methods, known as k-method, has the advantage of computational efficiency, even though from a physical point of view it is somewhat artificial.

In the k-method, structural damping is introduced as $\omega_h^2(1+ig)$ and $\omega_\alpha^2(1+ig)$ in heave and angle of attack states respectively, where g is the structural damping coefficient. In addition, pure sinusoidal motion is assumed ($\omega = \omega_R$ and $\omega_I = 0$). For a given speed, the structural damping required to sustain pure sinusoidal motion for each aeroelastic mode is then calculated.

The computational advantage of this approach is that the aerodynamic forces only need to be determined for real frequencies. The disadvantage however is that if, for example, a system with no structural damping is stable at a given airspeed, the calculation results in negative values of g. A negative value of structural damping does not have any physical explanation and cannot be interpreted directly in terms of ω_I. Indeed, for any given system with some prescribed damping, only at the flutter airspeed ($U = U_F$; where $\omega = \omega_R$ and $\omega_I = 0$) will the mathematical solution be physically meaningful.

Plant Description

Physical parameters of the aeroelastic structure were identified through ground testing as part of an aircraft airworthiness certification. The tests were done as part of a commercial contract between RMIT University and an aircraft manufacturer. Unfortunately the commercial contract prohibits the author from identifying the aircraft.

The aeroelastic values identified in ground testing are shown in Table I.

TABLE I

PHYSICAL PARAMETERS OF THE AEROELASTIC STRUCTURE

Parameter	Description	Value
w_h	heave natural frequency	13.25
w_a	torsional natural frequency	25.38
w_b	aileron natural frequency	9.56
a_h	position of aileron	-0.28
x_a	wing C.G. to mid-chord	0.2
x_b	aileron C.G. to mid-chord	0
m_x	mass	10.40
I_{ax}	wing moment of inertia	1.12
I_{bx}	aileron moment of inertia	0.0607
span ail	aileron span	2.15
semi span	wing semi-span	4.74
chord	wing chord	1.22
c	aileron chord	0.5

Derivation of Equations of Motion

The equations of motion were previously derived and published by the author. Details of the derivations of the equations can be found in (Zadeh, 2004). The equations have been modelled for simulation (see Figure 4), and are explained below.

Design Specifications

Aerospace structures are designed to avoid regions of operations that may lead to aeroelastic instabilities, as such instabilities may have catastrophic results. Therefore traditionally, active control of aeroelastic behaviour has not been widely adapted in the industry. As on-board computational power has been increasing and becoming more robust over the past few years, there has been some recent research in application of active aeroelastic controllers. One of the more difficult part of design of such controllers is calculation of the critical (flutter) speed.

Calculation of flutter speed, as explained earlier, is usually based on one of several indirect methods. The k-method is used for this research, as it has the advantage of computational efficiency, even though from a physical point of view it is somewhat artificial.

The aeroelastic system was modelled and assembled in Simulink software environment, as shown in Figure 4. The Simulink model was placed inside a block to allow it to be easily embedded into other Simulink models (Figure 5). The block model was then used to construct an uncontrolled simulation system, shown in Figure 6. This is the model that is used in simulation, allowing study of behaviour of the uncontrolled system.

FUZZY LOGIC CONTROLLER

A nominal fuzzy logic controller was designed and implemented following the procedure set out in (Zadeh, 2002; Zadeh, 2003; Zadeh, 2004). The universe of discourse of each input was covered using seven membership functions. Similarly seven membership functions were used for the output.

A Simulink model of the controller was constructed and linked to the model shown in Figure 6, forming part of the complete model shown in Figure 7. Saturation of inputs and physical limitation of maximum available control authority are also implemented in the model.

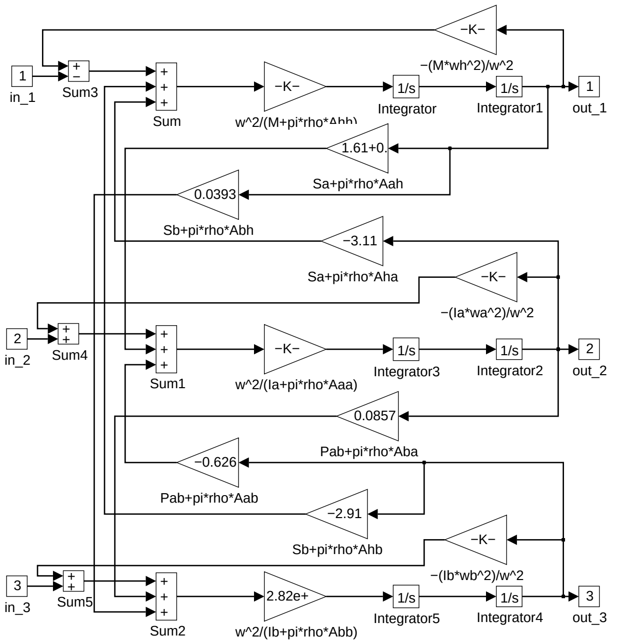

Fig. 4. Detail of the Aeroelastic System

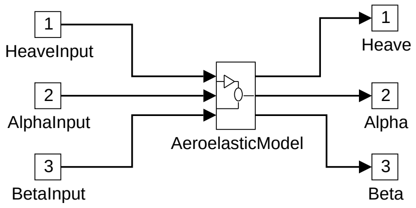

Fig. 5. Aeroelastic System Block

Excessive movement of the wing and wing components are known to accelerate fatigue and reduce ride quality. The controller therefore needs to generate control commands to reduce the induced vibrations. These requirements, plus some operational requirements, were considered in designing the fuzzy logic controller.

SIMULATION RESULTS

Flight through a gusty environment was simulated by feeding the system a step input in heave direction. Response of the system to the step input is depicted in left-hand pane of Figure 8.

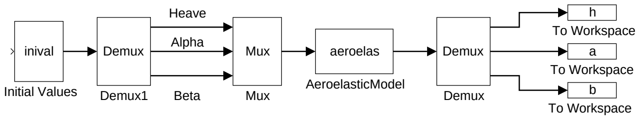

Fig. 6. Block Diagram of the Aeroelastic System

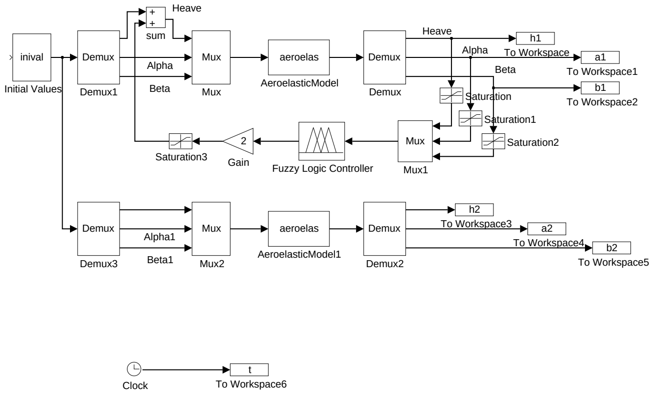

Fig. 7. Simulation Model of the Aeroelastic System

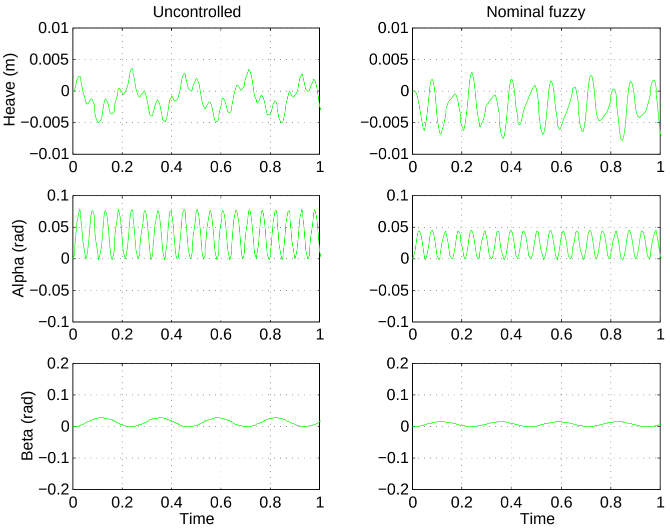

Fig. 8. Response of the Aeroelastic System With the Nominal Fuzzy Logic Controller

As is evident in Figure 8, the step input induces vibration in all the three states of the system. This is the result of coupling of aeroelastic modes. Note that at flutter speed, the energy extracted from the air stream is equal to the structural damping. Hence, once vibration induced, amplitude of vibration does not decrease over time.

Response of the system under control of the fuzzy logic controller is plotted in right-hand pane of Figure 8. The Figure shows that the nominal fuzzy controller successfully reduces amplitude of the induced vibration in all three degrees of freedom. Reduction in amplitude of vibration in heave is not as pronounced as the other two degrees of freedom of the system. This is because the amplitudes were not normalised for calculating the cost function; whence the optimisation routine places a much higher emphasis on reducing vibration amplitude in the angle of rotation and the aileron movements. This is in line with best practises commonly used in the industry.

CONCLUSION

Aeroelastic instability was briefly introduced. The nonlinearity and complexities of an aeroelastic wing was explained in order to demonstrate difficulties of designing controllers with good performance for such a system. A real-life wing was used as the testbed for designing a nominal fuzzy logic controller. Simulation methodology and simulation results of the nominal controller were presented.

Simulation results demonstrate suitability of fuzzy logic as control mechanism for the nonlinear and complex testbed.

The nominal controller has been used as the basis for designing an optimised controller using a constrained, multi-criteria, stochastic optimisation scheme. Because of publication space limitations, the optimisation of the controller has been submitted as a separate, follow-on, publication (Zadeh, 2005).

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