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

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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 (Zadeh, Scott and Wood, 1997; 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. Because of publication space limitations, modelling of the testbed and design of the nominal controller are submitted as a separate, lead-on, publication (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.

FLCs are usually designed by providing expert input to the controllers in the form of linguistic phrases. 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) 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).

Optimisation of fuzzy controllers and the limitations associated with it are considered in the following sections, followed by the specific area this research aims to address. Choosing a constrained, multi-criteria, stochastic optimisation scheme, the methodology used in optimising the nominal fuzzy controller

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is then explained.

CONTROL OF AEROELASTIC SYSTEMS

Aeroelastic phenomena occurs due to a combination of inertia, aerodynamics, and elastic forces. For decades 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. Aerodynamic forces, for a given configuration, increase rapidly with velocity, while the elastic stiffness is independent of the velocity, so 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 is usually referred to as dynamic aeroelastic instability.

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 analyse (and control) analytically.

A model of the structure is developed for the purposes of high-fidelity simulation and evaluation.

A nominal fuzzy logic controller was designed and implemented for the model of the structure. The design of the nominal control is covered in more detail in the lead-on publication (Zadeh, 2005).

The nominal controller has been used as the basis for designing the optimised controller.

The model of the structure was coupled with the nominal, and then with the optimised controller. Flight through a gusty environment was simulated, and results are presented. Finally, performance of the nominal and optimised controllers are compared.

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 also exist 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 and Design Specifications

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. Solution of the flutter equations is presented in the lead-in paper (Zadeh, 2005), and is covered in detail in (Zadeh, 2004).

Figure 1 shows the aeroelastic system as modelled in Simulink software environment.

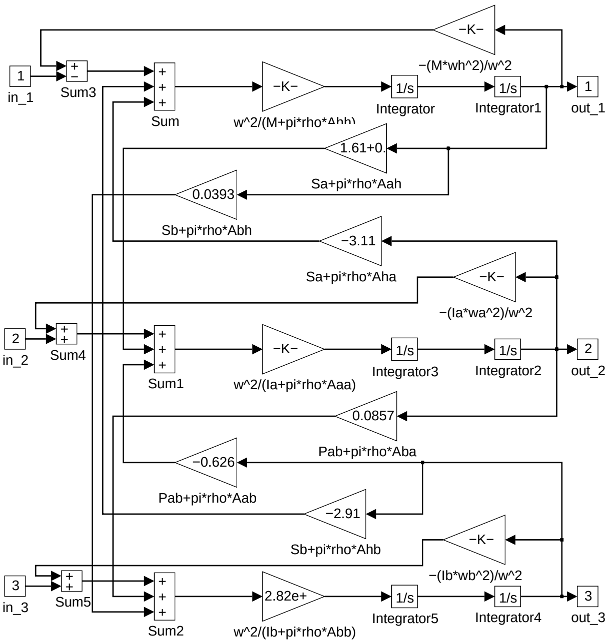

Fig. 1. Details of the Aeroelastic System

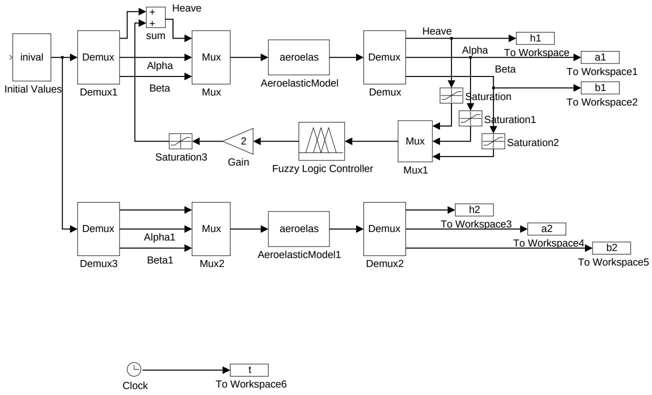

Fig. 2. Simulation Model of the Aeroelastic System

FUZZY LOGIC CONTROLLER

A nominal fuzzy logic controller was designed and implemented following the procedure set out in the lead-in publication (Zadeh, 2005).

Complete simulation model used is shown in Figure 2. Saturation of inputs and physical limitation of maximum available control authority are also implemented.

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.

OPTIMISATION OF FUZZY CONTROLLERS

Classical optimisation theory is well developed for deterministic problems and those of low to moderate dimension, limiting its application in contemporary problems. However, being inherently highly nonlinear transfer functions, fuzzy logic controllers pose a challenge to classical optimisation methods.

It is well known that design of fuzzy logic controllers with good or even acceptable performance depends very much on physical insight of the control system designer (Zadeh et al., 1997; Zadeh, 1998). While this can be viewed as an advantage of the controller, it has contributed to (mis)conception that this technique suffers from less scientific basis and less repeatable design process.

To address these shortcomings, optimisation of fuzzy logic controllers has been an active area of research in the past few years. Some novel forms of optimisation, such as genetic algorithms, as well as some traditional ones, such as gradient method, have been examined in literature.

Numerical optimisation has been applied to optimisation of FLCs as early as 1992. Shehadeh and Lea (Shehadeh and Lea, 1992) used genetic algorithms (GAs) in fine tuning of Membership Functions of an FLC to perform translational and rotational control of a space vehicle. Also in 1992, Smith and Comer (Smith and Comer, 1992) developed a method based on cell state-space concept to calibrate an FLC, while at the same time, observing some fuzzy optimisation constraints.

In 1993, Hwang and others (Hwang, Tao, Thompson and Paz, 1993) compared an FLC to an optimal PD controller, and found the FLC providing better performance as well as being more robust. In the same year, Ramaswamy and others (Ramaswamy, Riese, Edwards and Lee, 1993) used a simplified Kalman filter and a suboptimal filter in order to tune two FLCs. This work was also one of the earlier works observing good stability and performance robustness characteristics of the optimised FLC for a wide range of operational conditions.

Homaifar and others (Homaifar, Bikdash and Gopalan, 1997), basing their work on GA techniques, implemented a computer procedure for designing a hierarchical hybrid fuzzy-PID controller. Their approach combined GA, expert knowledge, and fuzzy learning by example.

Chung and Chiang (Hung-Yuan Chung, 1997) used reinforcement learning and GA to optimise a multilayer neural network model of an FLC. The process was able to generate the fuzzy control rules and refine the Membership Functions (MFs) at the same time. Bennis and others (Bennis, Ortega, Chu and Mulder, 1999) extended the use of reinforcement learning and GA in optimisation of FLCs by applying the technique in finding the best sets of MFs and the most suitable rule database. Use of reinforcement learning was further extended by Kang and Bien (Kang and Bien, 2000) for multi-objective optimisation of an FLC. Taylor and Sheng (Taylor and Sheng, 1998) introduced a two step method, whereby the first step generates an initial FLC, and the second step optimises the FLC by a recursive optimisation technique.

Li (Li, 1994) used a neural network to optimise placement of MFs of an FLC. Also reported in the same paper was a number of simulation results involving both step and tracking control of a nonlinear system.

Another approach in optimisation of FLCs was introduced in 1994 by Foster and Khambhampati (Foster and Khambhampati, 1994). In this approach, the number of MFs was optimised. Krishnakumar (Krishnakumar, Gonsalves, Satyadas and Zacharias, 1995) used GA to optimise both distribution and number of MFs of a FLC. Simulation results showed the optimised FLC, used for longitudinal stability augmentation of a model F/A-18 fighter aircraft, possess good robustness qualities.

The use of GAs in optimisation of FLCs has gained momentum since then, and to date there exists a large body of literature devoted to the use of GA for optimisation of FLCs.

More recently, Pahm and Castellani (Pham and Castellani, 2002) proposed an algorithm that used GA for automatic generation of the knowledge base for FLCs. Pal and others (Pal, Pal and Pal, 2003) proposed a method that used GA in order to optimise an FLC; the method was very efficient in that it could find rule sets containing less than 5% of all possible fuzzy rules, and only took a few steps to balance the system over the entire input space.

Probably the optimisation approach closest to the focus of this research was taken in 1995 by Akbar and Parra-Loera (Akbar and Parra-Loera, 1995). They used simulated annealing for designing MFs of a FLC, and applied it to the truck backup problem. Their approach, however, was very limited in that it required symmetric distribution of MFs and was only shown to apply to very simple control problems.

Lin and others (Lin, Bao and Braasch, 1999; Whorton, Lin, Bao and Braasch, 1999) covered vibration control of a flat testbed using FLCs. Proposing a method that converts optimisation of an MIMO controller to optimisation of a number of scaling factors, Whorton and others (Whorton et al., 1999; Lin et al., 1999) used a very simple flexible structure for vibration control simulation studies.

OPTIMISATION IN THIS RESEARCH

Having discussed numerical optimisation of FLCs, and extended the discussion to (partially) include application of the optimised FLCs in vibration control, it is clear that there is a need for a comprehensive optimisation methodology of fuzzy logic controllers for highly nonlinear problems with real-life complexities, such as that of control of general flexible aerospace structures.

An aerospace structure must perform well over a range of operating conditions, from static operation through to maximum speed flight. The design space has many local minima and is also of a high dimensionality. The result is a formidable design problem requiring an optimiser capable of efficiently handling local minima and numerous design variables.

Traditionally optimisers rely on a good starting point to obtain a solution or even to converge (and the large number of variables increases the difficulty of guessing a good initial design). Thus, an additional requirement for this study is to use an algorithm which will obtain an acceptable solution without a good initial starting point. Furthermore, the optimiser must be robust, as the computational expense of objective function calculation makes intermittent failure unacceptable.

Solution to this problem is to use an unconstrained optimisation method known as Simulated Annealing (SA). This amounts to a stochastic search over a cost landscape, being directed by noise which is gradually reduced during convergence. Details of the theory involved are explained in more detail by Drack and Wharington (Drack and Wharington, 1998; Drack, 2000). The analogy to annealing derives from this noise being akin to the arrangement of states within a cooling metal.

There are several reasons for not adopting a more traditional calculus-based approach to this design optimisation problem. Firstly, these approaches rely on gradient information which is supplied either analytically or calculated numerically. For engineering applications in general, and aeroelastic structures in particular, analytical gradients are very rarely available, thus numerical methods must be employed introducing the possibility of numerical error. Furthermore, the cost function must be continuous to the first or second derivative, depending on the method used. These optimisers are also not suitable for design variables of integer value, such as the number of MFs for example, as gradients become infinite. Also, their tendency to become trapped in local minima is well known (Gage, 1994). SA does not calculate or estimate gradients, thus is free from these restrictions.

Another problem which adversely affects calculus-based methods is the need for a good initial guess to the solution (Arora, 1989). Convergence in these methods is often not possible or is unreliable if the starting point is poor. This becomes a serious issue in design spaces of higher dimensionality, where an initial guess made by the designer may not seem unrealistic. Sometimes even intuition in finding a good starting point fails due to the large number of variables.

The primary disadvantage of SA is its poor performance in shallow valleys, which may well occur in the vicinity of optima. This property is a consequence of the algorithm's stochastic sampling. In these regions, calculus based optimisation is far superior in converging to the exact value of solution.

OPTIMISATION METHODOLOGY

The model of the aeroelastic structure, developed earlier, was used as basis for the optimisation. The system was simulated for 5 seconds. A Runge-Kutta 5^{th} order method of integration with varying step size was used. Minimum and maximum step sizes were set to 0.0001 and 1 respectively. At each interval, heave, angle of attack, and aileron deflection were calculated and recorded. These values were used to calculated a cost function. Note that the values used in calculation of the cost function were not normalised.

Simulated annealing optimisation method was used to minimise the cost function. This was done by modifying the importance (height) of the controller's membership functions.

To gain better understanding of effect of the change of importance of the membership functions on the overall performance of the controller, weight of the first 20 MFs were chosen as optimisation variables. Weight of MFs of the optimised controller are plotted in Figure 3.

SIMULATION RESULTS

Flight through a gusty environment was simulated by feeding the system a step input in heave direction. The simulation was run three times; once uncontrolled, once with the nominal, and once with the optimised controller.

Response of the uncontrolled system to the step input is depicted in left-hand pane of Figure 4. Results of the nominal controller is shown in the centre pane and those of the optimised controller in the right pane. Heave, angle of rotation, and aileron deflection are shown from top to bottom.

As is evident in Figure 4, 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 speeds just before the onset of flutter, 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.

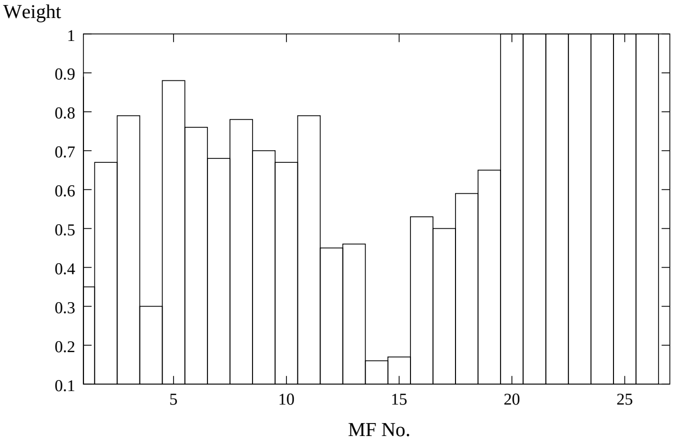

Fig. 3. Optimised Weight of the Membership Function of the Controller

The Figure shows that the nominal fuzzy controller successfully reduces amplitude of the induced vibration in all three degrees of freedom.

Simulation results also show great performance improvements for the optimised controller over that of the uncontrolled system, as well as that of the one with the nominal fuzzy controller.

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 reduction of vibration amplitude in the angle of rotation and the aileron movements.

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 uncontrolled system, and nominal and optimised controllers were presented.

The nominal controller has been used as the basis for designing an optimised controller using a constrained, multicriteria, stochastic optimisation scheme.

Simulation results demonstrate suitability of the methodology for optimisation of fuzzy controllers of a highly nonlinear testbed with real-life complexities. Because of publication space limitations, modelling of the testbed and design of the nominal controller are submitted as a separate, lead-on, publication (Zadeh, 2005).

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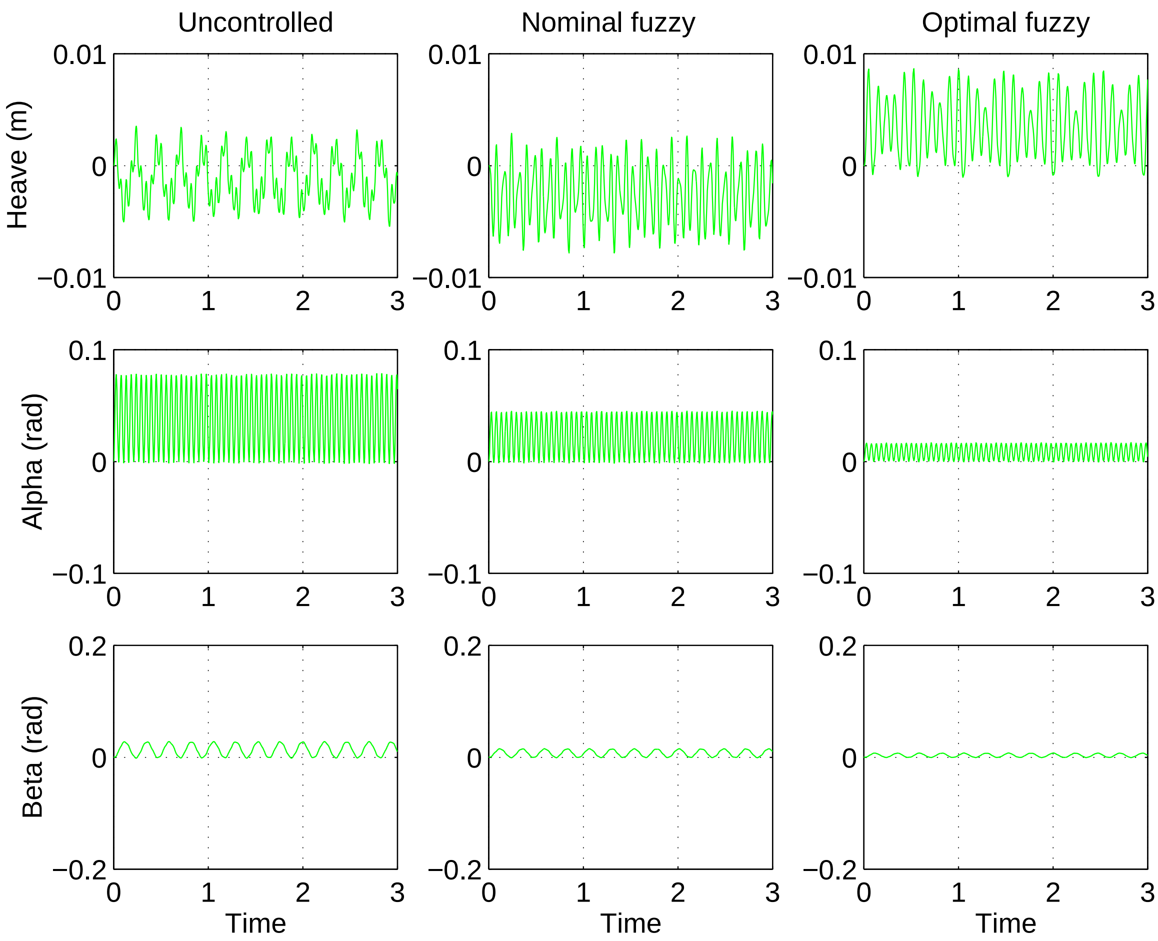

Fig. 4. Response of aeroelastic system with fuzzy logic controller. From top to bottom: Heave, angle of attack, and aileron deflection of the wing. From left to right: response of the system with no active control, with the nominal fuzzy controller, and with the optimal fuzzy controller respectively.

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