Proceedings of the International Conference on Aerospace Science and Technology
26-28 June2008, Bangalore, India

Extended Abstract

Eigenstructure Control: A Flight Vehicle Handling Qualities Design Tool

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1. Introduction

With the development of high reliability sensors, computers and actuators, it is now possible to build flight vehicle control systems with extraordinary performance. Indeed full authority fly-by-wire flight vehicles using feedback controllers can substantially mask the basic airframe dynamic characteristics and consequently its performance limitations. These technology developments in turn have brought into focus the role of multivariable control system design methods to evolve complex multi-loop systems using multiple sensors and control effectors. Multivariable control techniques are now being demonstrated in experimental flight research programs. It is thus reasonable to expect that these methods will be used in flight vehicle control design of production aircraft as increased sophistication in airframe design and performance is sought. Among the many control techniques available for such design, **Eigenstructure Control** techniques offer some unique advantages since the flight vehicle handling qualities requirements originate in the **modal control** framework. The present study explores methods to adapt this method for deriving practical flight control laws.

2. Eigenstructure Control

It is now well known that for an n-state, m-input controllable system, in addition to assigning all the n-eigenvalues, (m-1) entries in each eigenvector can be arbitrarily assigned using state variable feedback [1]. Since eigenvalues and eigenvectors together characterize the dynamic response of a system, this property results in an elegant parameterization, in terms of the closed loop eigenstructure, for the selection of the n*m state feedback gain elements. When all states are not available for feedback (which is usually the case), two options are available: i) an output feedback control design [2], with its attendant reduced degrees of freedom or ii) a minimal order dynamic controller design to reconstruct the state feedback design [3]. Finally for pilot relief functions (auto pilot), explicit model following controllers need to be employed. This is especially true for designing decoupled multi-axis helicopter controllers. In the present study, all of these methods will be used in the development of aircraft and helicopter control laws.

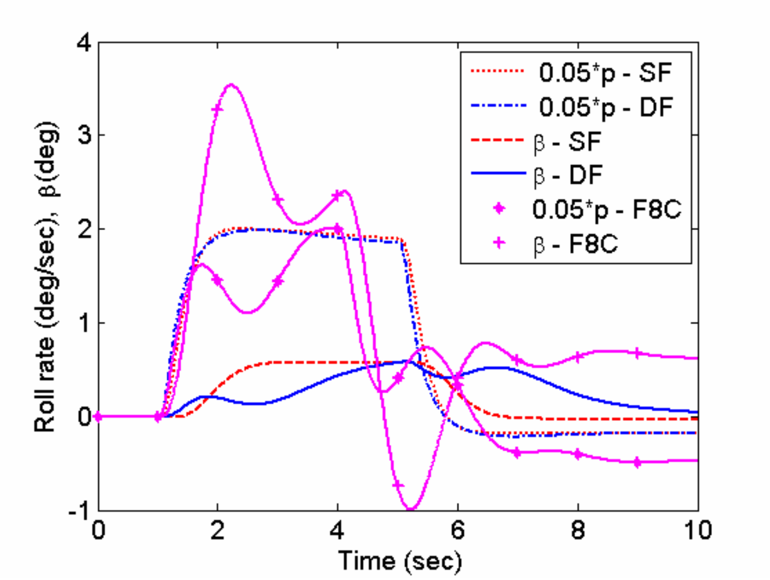
3. Aircraft Lateral–Directional Handling Qualities Design

The aircraft dynamics is characterized by state variables: roll rate (p), yaw rate (r), sideslip angle (β) and bank angle (φ). The control variables are aileron (δ_a) and rudder (δ_r). The aircraft motion is characterized by modes described as roll (convergent), spiral (convergent/divergent) and Dutch roll (oscillatory). The handling qualities requirements constituting eigenvalue specifications are improved Dutch roll damping, crisp roll mode response. The primary handling qualities specifications requiring eigenvector modification is improved turn co-ordination and reduction of Dutch roll mode contamination in roll rate response. Turn co-ordination implies minimum yaw coupling in roll entries and exits using aileron control and can be quantified as minimizing sideslip excursions. The design process involves first designing a state feedback controller using p, r, β and φ as feedback variables. In addition an aileron to rudder interconnect gain is used for improving the turn co-ordination. This results in a benchmark reference design. Since sideslip and bank angle sensors are not preferred for feedback, due to reliability considerations, the state feedback performance is achieved using a dynamic feedback control law using p, r, $\dot{\beta}_e$ and β_e as feedback variables. The estimates of sideslip rate ($\dot{\beta}_e$) and sideslip (β_e) are given by:

$$\dot{\beta}_e = \left(\frac{-s}{s + p_W}\right)(r - p\alpha), \beta_e = \frac{p_L}{s + p_L} n_y \quad (1)$$

The signal $(r - p\alpha)$ in (1) is the stability axis yaw rate and α is the angle of attack. The lateral acceleration (n_y) is a good surrogate signal to derive sideslip information. Fig 1 shows the improvement in turn co-ordination using state and dynamic feedback for an F8 aircraft model at a high angle of attack (α = 15.5 deg) condition. It is seen that the Dutch roll contamination in roll rate response of the basic F8 aircraft has been eliminated by eigenvector modification. Synthesizing mode-decoupled eigenvectors has also reduced the large sideslip excursion of the basic aircraft.

Fig. 1 Roll rate (p) and Sideslip (β) Response for Aileron input
(SF: State Feedback, DF: Dynamic Feedback, F8C: F8-Aircraft)



4. Helicopter Handling Qualities Design

The helicopter, from a control point of view, is a very complex machine exhibiting substantial pitch, roll and yaw inter-axis coupling. The presence of the rotor adds additional dynamic coupling to the rigid body dynamics. Pilot relief functions in the form of attitude command / hold functions become essential when the vehicle has to be operated in degraded Usable Cue Environment (UCE). As in the case of aircraft, the helicopter handling qualities requirements can be quantified in terms of modifying the **Eigenstructure**. The major design challenge is the reduction of inter-axis coupling. The helicopter rigid body states are inertial rates (p, q, r), translational velocities (u, v, w) and inertial attitudes (θ, φ). The controls are collective (δ_c), longitudinal cyclic (δ_a), lateral cyclic (δ_e) and pedal (δ_p).

The design process adopted in the present study consists of the following steps:

Step 1. Design a control law using rigid body state feedback to δ_a, δ_e, and δ_p, along with control inter-connects, to minimize the inter-axis cross coupling using the ADS-33E-PRF frequency domain criteria [4].

Step 2. Design a 4th order dynamic compensator, using only inertial rate sensors (p, q and r) as feedback variables to replace the state feedback law in step 1.

Step 3. Design a tunable explicit model following controller to provide a decoupled Pitch attitude (δ_a) / Roll attitude (δ_e) Command system for use in degraded UCE.

A brief summary of the performance of the helicopter augmentation system using a model of a BO-105 helicopter is given below

Fig. 1 illustrates the improvement in pitch / roll inter-axis coupling using feedback. The Level-2 characteristic of the BO-105 helicopter has been improved to Level-1. Fig.2 demonstrates the cross-axis response reduction achievable using feedback controllers. Since the pilot longitudinal (lateral) cyclic controls directly command the pitch (roll) rate, the feedback-augmented system is termed as a **rate response** type system. In good UCE situation (UCE=1), this system is known to be adequate for most of the Mission Task Elements (MTE).

Fig. 1 Pitch / Roll Inter-axis Coupling (ADS-33E-PRF)
(SF: State Feedback; OBS: Observer)

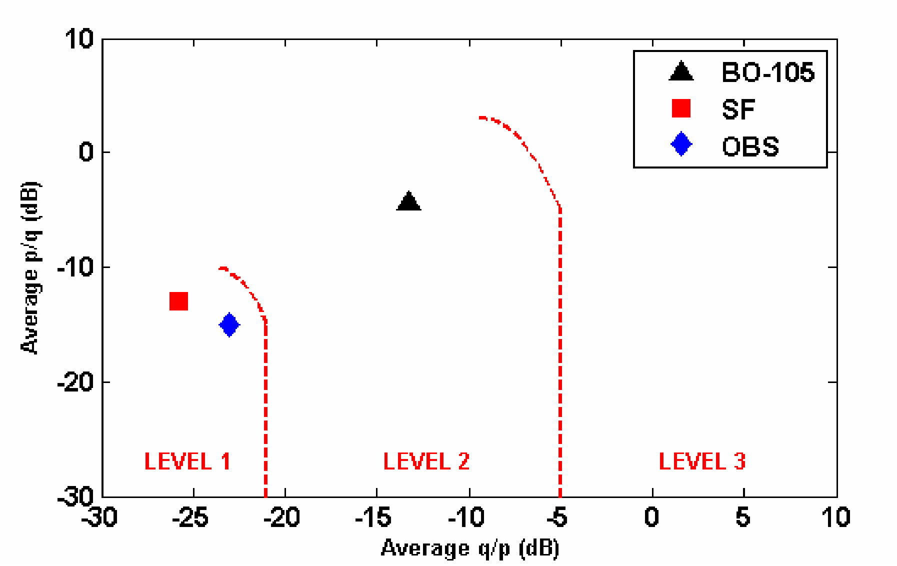
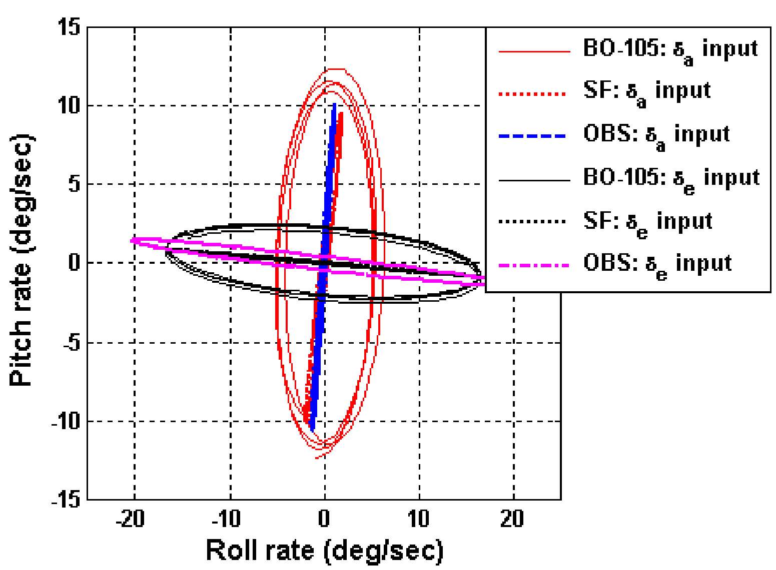


Fig. 2 Feedback Controller Decoupling Performance
Response type: Rate, (Sinusoid Input)



As indicated earlier, for degraded UCE situations, pilot relief functions such as Attitude Command and hold (ACAH) systems are essential. This is achieved using an Explicit Model Following (EMF) controller in the command path. The EMF design can again be formulated as an Eigenstructure assignment problem. Fig, 3 and Fig. 4 show the performance of an EMF design for commanding the pitch and roll attitude with minimum off-axis response. The hold function is typically realized using a proportional plus integral feedback of the respective commanded attitudes.

Fig. 3 EMF Controller Decoupling Performance
(Response type : Pitch Attitude Command)

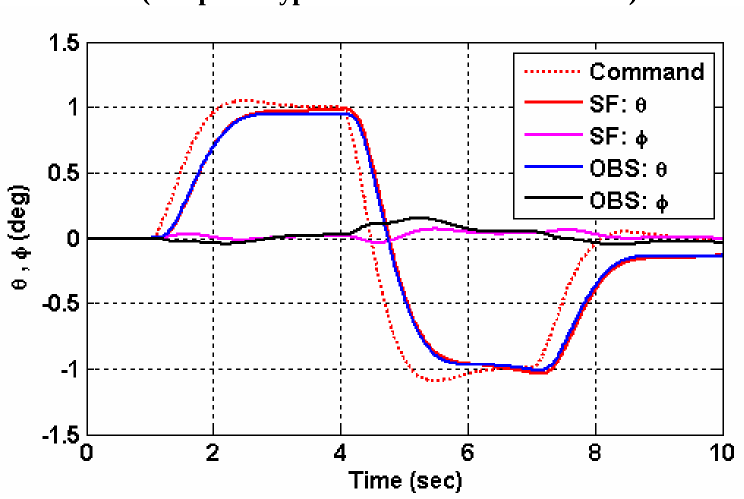
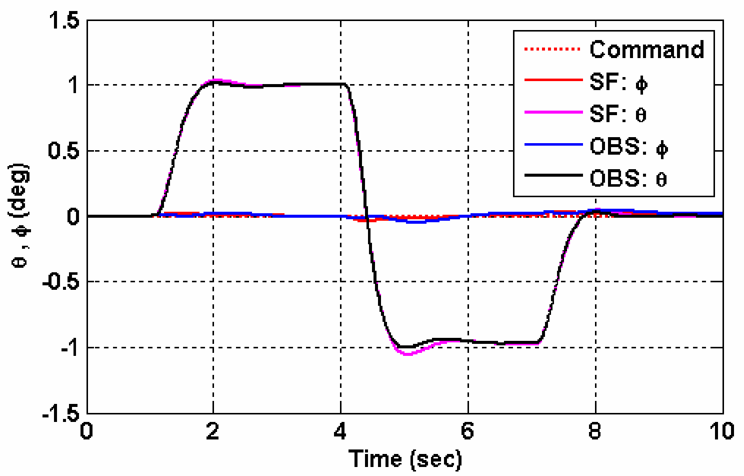


Fig. 4 EMF Controller Decoupling Performance
(Response type : Roll Attitude Command)



5. Conclusions :

The present study demonstrates that the core concept of **Eigenstructure Control** can be adapted to related design problems such as observer based dynamic compensators, implicit and explicit model following controllers. This results in a suite of algorithms which can be used to address complex control system design situations. The helicopter handling qualities design is one such example.

6. References :

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