Epilogue

An astute engineer,
Irrespective of the design methodology,
Finds good solutions.

Eigenstructure control, as a multivariable synthesis tool, has fascinated many researchers, including this author, for many years. Application studies, mostly in flight control, have revealed the many facets of this interesting theory. The computational simplicity and the direct relation of the synthesis parameters to the dynamic response of a system has been the driving force for the method to become attractive for feedback design. The application of the method for the design of the A-320 lateral-directional autopilot in the late 80’s and the NASA F/A-18 HARV lateral-directional control laws during mid 90’s are two notable applications culminating in successful flight tests.

However there has been still some reluctance in the aircraft industry to infuse multivariable control techniques into their design practices. The NATO report [1] is an excellent reference document that details the complexities of flight critical control law design and examines the role multivariable control design methodologies need to play in the design of future generation combat aircraft. In general some of the apprehensions, perhaps justifiable, cited against the use of multivariable control methods are:

1) Multivariable design methods, using generalized controller structures, do not provide good insight into the design process. Specific controller structures built on intimate knowledge of flight mechanics are essential for evolving successful flight control designs.

2) The multivariable controller structure invariably has too many design parameters and with the design process being iterative in nature, tuning of these parameters becomes quite cumbersome and time consuming and also results in loss of physical insight.

3) Aircraft design techniques, primarily based on classical control concepts, have been well established. What additional advantages do the ‘modern’ control design techniques really offer to justify their use?

The approach taken in this book to address these issues has been:

a) Construct, simple to use, synthesis algorithms that retain the transparency between design parameter change and consequent response deviations. The eigenstructure synthesis formulation, as developed in this book, does result in minimal set of tunable parameters required for iterative design refinement process.

b) Build the controller structure from the simplest possible, based on flight mechanics analysis and progressively increase the complexity as the demand for better system performance is deemed essential.

c) Formulate suitable non-linear constrained optimization problems to fine-tune those design parameters that cannot be easily determined by direct synthesis. This aspect of using eigenstructure synthesis algorithms, as a core part of an overall optimization problem, has not been well emphasized in the literature and thus leading to some of the apprehensions cited earlier.

d) Based on the above design process, demonstrate the utility of the approach by detailed design studies of aircraft and rotorcraft flight control laws to meet stringent dynamic performance requirements as defined in the appropriate handling qualities specification documents (Aircraft: MIL-HDBK-1797; Rotorcraft: ADS-33E-PRF)

The principal findings of the studies in this book can be summarized as follows:

1) The algorithm developments in chapters 2-4 highlight the concept of direct eigenvector element assignment that preserves the transparency of relation between design parameters and system response, an essential characteristic alluded to earlier. In chapter 5, the numerical ill conditioning of the matrix of eigenvectors is shown to be an indicator of robustness of design. This leads to the definition and properties of modal robustness metrics. The optimization of these robustness metrics forms the basis for the design of robust feedback systems. The importance of combined optimization of both eigenvalues and available eigenvector freedom (not usually considered in application papers) to improve modal robustness is highlighted.

2) The formulation of modal canonical observer design as an eigenstructure assignment problem in chapter 6 leads to the determination of minimal dynamic order 'functional' observers that estimate a state variable feedback control law. This results in a low order 'dynamic compensator' based design that replicates a benchmark state feedback solution. The functional observers also find applications in sensor fault detection and isolation schemes wherein the analytically derived sensor response from the observer is used to identify a faulty hardware sensor in a dual redundant hardware sensor set.

3) The two-degree-of-freedom controller structure consisting of forward path and feedback elements is a generic structure used in multivariable control. The novel concept of *tunable* command generator tracker proposed in chapter 7 plays an important role in the forward path controller design.

4) Aircraft lateral-directional control law design example in chapter 9 introduces the concept of building the controller complexity starting from the traditional roll / yaw damper structure to a more complex dynamic compensator design based on eigenstructure synthesis. This study reveals the additional benefits that accrue as the controller design parameter set is progressively increased. The analysis of eigenvector structure properties of the Dutch roll mode enables non-interacting aileron and rudder loop response optimization design possible. The property of the invariance of the eigenstructure assignment to the aileron to rudder interconnect gain again leads to another non-interacting design optimization.

5) In chapter 10, the aircraft pitch axis control problem is addressed. With only a single input available for control, it is shown that the traditional controller structures such as pitch rate command / attitude hold can be formulated as an eigenvalue assignment problem. If the aircraft is equipped with multiple control surfaces, the pitch axis control can be cast as a model following control problem. The study reveals the benefits of using multiple inputs in: i) improving the pitch axis handling qualities using an implicit model following design and ii) design of advance control modes such as ‘pitch pointing’ using the explicit model following controller structure. The role of the tunable command generator tracker design in arriving at optimal design is again highlighted.

6) The rotorcraft control law design study in chapter 11, exemplifies the need for using a generalized controller structure to meet the exacting handling qualities specifications. The rotorcraft exhibits significant inter-axis coupling and identification of a specific controller structure, as was possible in aircraft examples of chapters 9 and 10, especially to reduce the inter-axis cross coupling, becomes difficult. This is especially true since use of acceleration sensors as surrogate signals for flow angles, as in case of aircraft, is not feasible. This is due to the corruption of rigid body accelerations with rotorcraft vibration modes. Thus use of the generic two-degree-of-freedom multivariable controller structure becomes inevitable. The design study in chapter 11 reveals that a compensator based controller using only inertial rate sensors as feedback sensors can meet the handling qualities specification and in particular the reduction of the pitch / roll cross axis coupling. The dynamic compensator consists of a fourth order functional observer that estimates a state variable feedback design tuned to meet handling qualities design objectives. A forward path controller using the tunable command generator tracker concept is used to design a multi-axis decoupled attitude command system.

7) The flutter control problem discussed in chapter 12 reveals that a fundamental understanding of the flutter phenomenon from a control point of view suggests that no more than a second order compensator is needed to stabilize each flutter mode. This concept has been experimentally demonstrated in a wind tunnel test of an aero-elastic wing model. The problem of stabilizing / improving the damping of multiple aero-elastic modes using eigenstructure control concepts are also highlighted.

In conclusion, in this book, an attempt has been made to present a unified suite of algorithms, based on eigenstructure control theory, for flight control law design. The use of this *design tool set* to evolve practical control laws for aircraft and rotorcraft to meet the handling qualities specifications has been demonstrated. The presentation of design results has been intentionally made extensive. The purpose behind this approach has been that a serious reader will be able to verify the intermediate design steps. Towards this end the entire state variable model and other hardware filter assumption details, that are required to reconstruct the results, have been included in the appendices.

Reference:

1. ANONYMOUS.: ‘Flight Control Design – Best practices’, December 2000, NATO RTO Technical Report 29