STABILITY AND CONTROL OF STOVL AIRCRAFT: THE DESIGN OF LONGITUDINAL FLIGHT CONTROL LAWS

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Abstract

Over the past three decades, the UK aerospace industry has carried out significant research into the development of short take-off and vertical landing (STOVL) technology, to enhance the performance and operation of the Harrier aircraft, and for possible application to future aircraft such as those being developed under the Joint Strike Fighter (JSF) programme. Some of this research has focused on aircraft handling and flight control for the transition between wing-borne and jet-borne flight. Following on from internal research at British Aircraft Corporation / British Aerospace (now part of BAE SYSTEMS) in the mid to late 1970s, further development work has been carried out in the 1980s and 90s in support of the UK's Vectored thrust Advanced Aircraft flight Control (VAAC) Harrier and Integrated Flight and Propulsion Control System (IFPCS) programmes. This paper contains a short review of STOVL aircraft longitudinal flight control law design, and how basic feedback control schemes can be used to influence the aircraft's response and hence its handling qualities.

1 Introduction

BAE SYSTEMS, and its European partners, have achieved significant experience with fly-by-wire technology, through its application to high performance conventional take-off and landing (CTOL) combat aircraft, from the Tornado [1] through to the Gripen and the Eurofighter Typhoon [2]. In parallel with these production aircraft developments, significant research has been undertaken in applying fly-by-wire technology to STOVL aircraft. Throughout, emphasis has been directed at the specific area of providing excellent, safe aircraft handling in the launch and recovery flight phases. A number of project aircraft have been proposed and studied in detail, as potential future replacements of the Harrier aircraft. This work has progressed through active involvement in both national and international STOVL aircraft research and development programmes.

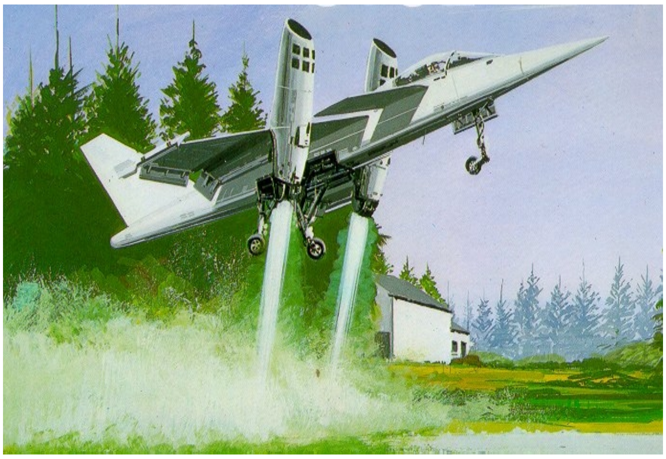

Figure 1: STOVL project aircraft P103

One of BAE SYSTEMS' first advanced STOVL aircraft projects was the P103 concept aircraft (Figure 1). It exhibited relaxed static stability to optimise its aerodynamic performance and also required the application of advanced flight control in the transition region and in jet-borne flight. This supersonic project aircraft was a canard-delta configuration with a two-poster augmented lift system and thrust vectoring capability, achieved by rotating the wing-mounted engine nacelles. The proposed aircraft was to have an integrated FCS/engine control system based on a development of the RB199 powerplant from the

Tornado aircraft. The aircraft did not have a reaction control system and in jet-borne flight the aircraft was controlled as follows: pitch control via symmetric nacelle deflection; roll control via differential thrust modulation; yaw control via asymmetric nacelle deflection. The nacelles included post-exit deflector flaps to allow fine pitch, roll and yaw control.

Control laws for this aircraft were developed and demonstrated through pilot-in-the-loop simulation in the early 1980s but the aircraft was not developed further, since more favourable configurations had been proposed. The P103 aircraft featured some interesting design challenges, such as how to deal with an engine failure at low speed, the aircraft's high potential for severe ground erosion and the effects of hot gas ingestion. These are very important design aspects for any STOVL aircraft.

The STOVL aircraft flight control experience gained on the P103 project was later utilised on the UK's Vectored thrust Aircraft Advanced flight Control programme [3], which is managed by the UK's Defence Evaluation and Research Agency. The aim of the project is to investigate low speed flight control, including the handling and cockpit display concepts intended for application to any advanced STOVL aircraft replacing the Harrier. As part of the project, BAE SYSTEMS designed an advanced longitudinal flight control law that was successfully demonstrated in a series of flight trials in the VAAC Harrier experimental research aircraft [4]. More recently, the longitudinal axis design has been complemented by BAE SYSTEMS designed lateral/directional control laws [5]. Both sets of control laws have been significantly developed to embody advanced features, through flight trials in conjunction with DERA.

Advanced STOVL aircraft control laws have also been developed as part of the UK's IFPCS programme [6,7]. These control laws are a further development of those demonstrated on the VAAC Harrier aircraft and have been applied to the P112C-6 project aircraft (Figure 2).

Figure 2: STOVL project aircraft P112C-6

The P112C-6 is an advanced supersonic concept aircraft with STOVL capability. It is based on a close-coupled canard-delta configuration, fitted with a three-poster remotely-unaugmented direct-lift system and a three-axis reaction control system, as shown in Figure 3.

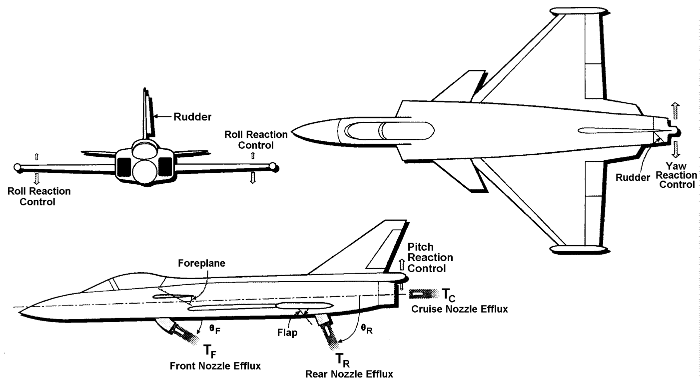

Figure 3: P112C-6 thrust vectoring arrangement

This is a more complex thrust vectoring arrangement than that of the Harrier, since the front and rear thrust vectoring nozzle angles are independently actuated and the thrust split between the front and rear lift posts can be varied.

This leads to some challenging design problems, such as correctly balancing the front and rear nozzle pitching moments about the aircraft's centre of gravity to maintain control, while at the same time ensuring that sufficient control authority is available to manoeuvre the aircraft and to reject atmospheric disturbances. The control laws for the P112C-6 aircraft [8] have been developed to a mature research standard, through extensive piloted simulation, including ship-borne operations. The thrust vectoring arrangement of the P112C-6 is broadly similar, at least in terms of its complexity, to that of the JSF programme's competing X-32 and X-35 demonstrator aircraft designs [9].

2 Background to control laws design

It has recently become apparent that much of the background to the design of STOVL flight control laws is not generally available, even inside industry. This paper is therefore an attempt to capture some of this background and is intended to serve as an educational paper. Perhaps these days, the root locus technique is considered to be out-dated and is rarely used, since automatic pole-placement methods are found to be more efficient. However, it is still believed that the root locus method has much to offer in terms of visualisation and understanding of the effects of feedback. It also helps a designer to appreciate the trade-offs associated with alternative feedback signals and the amount of feedback used. It is therefore used in this paper for this purpose.

A further reason for this paper is a concern that with the modern approach to designing flight control systems (or any other complex system) and the high degree of automation involved, some important insight into the design is being lost. The modern approach is to employ computing tools such as MATRIXx or MATLAB/SIMULINK, which make full use of the benefits of the 'block diagram' user interface. Models are assembled via the diagrams and usually include some standard functions from the toolset's library. From this stage onwards, there is a high degree of automation of the design process, underpinned by the tool's numerical techniques. Models are initialised (trimmed) by the optimisation of a cost function, and then they are linearised about the resulting steady state to produce small perturbation equations. A numerical solution of these equations is then used to determine the system's eigenvalues (poles or modes) at the steady operating point. There will be many modes for a complex dynamic system and the designer may not be able to relate these modes to the original block diagram or, more importantly, to the hardware and physics that is modelled within the diagram. This paper aims to help in this area, by explaining the origins of the typical closed-loop modes of highly augmented STOVL aircraft.

3 Linear control laws for CTOL aircraft

Before considering the more complicated case of the STOVL aircraft, it is worth reviewing the natural longitudinal 'rigid aircraft' modes of the CTOL aircraft and how these are affected by the feedback signals within its flight control system.

As a first example, a simple pitch rate feedback system is shown in Figure 4. If we exclude the integral and feedforward terms, then we have a simple proportional control law. This forms the basis of many analogue pitch stability augmentation systems, from the limited-authority systems implemented in Jaguar and Harrier to the Tornado aircraft's full-authority command and stability augmentation system [1]. In these inherently stable aircraft, one of the main design requirements is to improve the aircraft's handling by increasing the damping of the short-period response, across the flight envelope.

A typical root locus plot for the pitch rate feedback loop gain GL (with GP set to unity) is shown in Figure 5. A design value is chosen that is low enough to ensure the required gain and phase margins [10], but high enough to provide sufficient short period mode damping and a rapid and deadbeat g response (a feedforward term may be required). This figure shows the effect of the higher frequency 'FCS hardware mode' (typically 3.0 to 5.0 Hertz for a combat aircraft) which is usually associated with the actuation system's dynamics. This mode is related to the gain margin, in the sense that it is this mode that crosses into the right-half of the complex plane, when the loop gain is increased by the gain margin factor.

Having designed a satisfactory feedback loop, the command path filtering is then designed, to give good pitch tracking characteristics. A phase retard (lag/lead) filter is usually used for this purpose, with the design aim being to get zero drop-back in the attitude response [11]. A common error is to add a lag filter to the command path. Although this provides desirable attenuation in the higher frequency range, it introduces a detrimental phase lag penalty which delays the aircraft's angular acceleration response (an essential motion cue), outweighing any other benefit, and making the aircraft prone to pilot-involved oscillations. The phase retard filter provides the required attenuation but with minimal phase loss at the higher frequencies, retaining the pilot's vital pitch acceleration cues in response to his commands.

The inherently stable aircraft does not usually require an integral term in its controller in order to meet its dynamic design requirements. The pilot can easily perform any integral action, as he adjusts his stick position in order to attain the desired control surface position and the associated aircraft response. However, it is noted that the advantage of an integrator for a stable aircraft, is that it provides fairly constant static characteristics for varying configurations, such as due to different stores, fuel state, wing sweep etc.

Proportional plus integral control is particularly effective for the pitch control of a longitudinally unstable aircraft, with the integral action playing a major part in the stabilisation

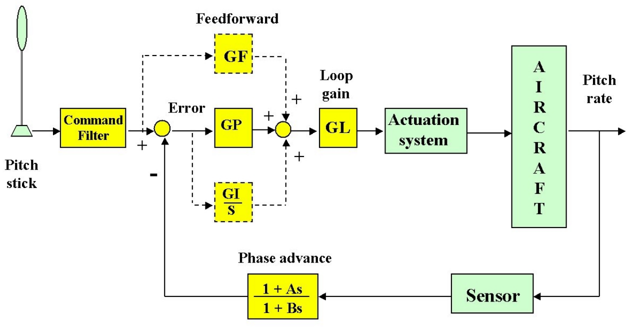

Figure 4: simple pitch rate feedback system

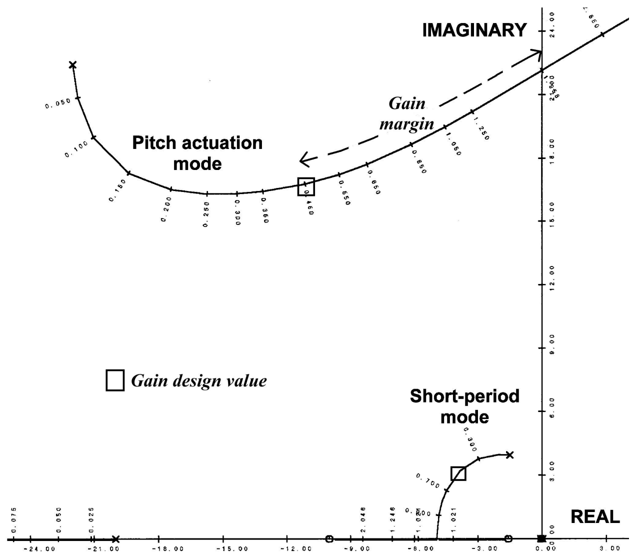

Figure 5: root loci for the loop gain for a stable aircraft

of the unaugmented aircraft's unstable short-period root. The integrator provides an automatic trimming capability as it acts to reduce the error between the commanded and measured aircraft responses. Such a controller structure formed the basis of the EAP's pitch control laws [12] and is typical of many other fly-by-wire aircraft including the F-16, X-29, X-31, Gripen and the Eurofighter Typhoon. Figure 6 shows the root loci for the pitch rate loop gain for an unstable aircraft with a proportional plus integral controller. As previously, the root locus technique can be used for determining the positions of the closed-loop eigenvalues. The root locus plot also shows the gain margins for the loop gain (GL), defined as the factors (increasing or decreasing) which, if applied to the design value, will lead to instability, as a pair of complex poles cross into the right-half plane. The phase margin is not visible from the root locus diagram and a frequency response is therefore necessary, to confirm that it is acceptable.

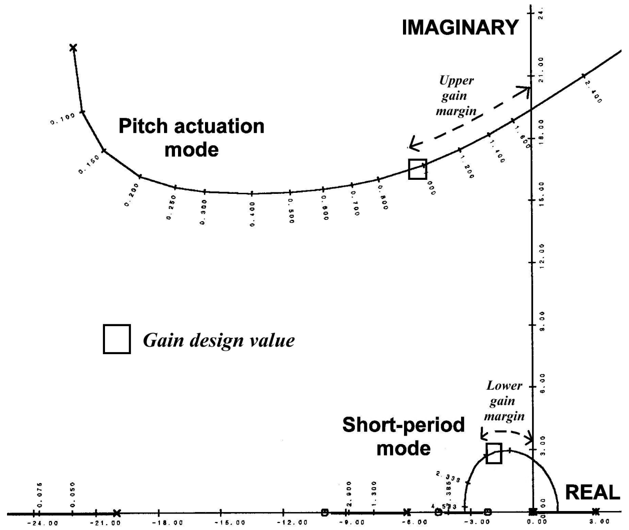

Figure 6: root loci for the loop gain for an unstable aircraft

As with the stable aircraft, the aim is to select GP and GI values (a 1:2 ratio is a good general guideline), and then to determine the GL value that will provide satisfactory stability margins and a satisfactory g response (where again, a feedforward term might be required). A major difference between stable and unstable aircraft is that a large enough reduction in the loop gain of the unstable aircraft's feedback will result in instability and therefore, the control system will have both upper (approximately 3.0 to 5.0 Hertz) and lower (approximately 0.2 to 1.0 Hertz) gain margins. Despite this difference, the time responses and handling qualities can be designed such that they are virtually identical for different aircraft stability levels: the naturally unstable aircraft can be made to fly exactly as if it were a stable aircraft - but with the performance benefits associated with relaxed static stability. Furthermore, with digital technology it is significantly easier, via gain scheduling, to optimise the handling qualities at each point in the flight envelope, for both stable and unstable aircraft.

4 Linear control laws for STOVL aircraft

4.1 The unaugmented aircraft

By definition, the fundamental difference between CTOL and STOVL aircraft is the capability of the latter to perform a short take-off and a vertical landing. During the transition from wing-borne flight to jet-borne flight, the aerodynamic lift force is progressively replaced with jet-lift as the airspeed is reduced. During the transition, dynamic pressure reduces and the response of the aircraft to aerodynamic controls becomes more sluggish, as the frequency of the short-period response is reduced. The flight path time delay also increases, making flight path control more difficult.

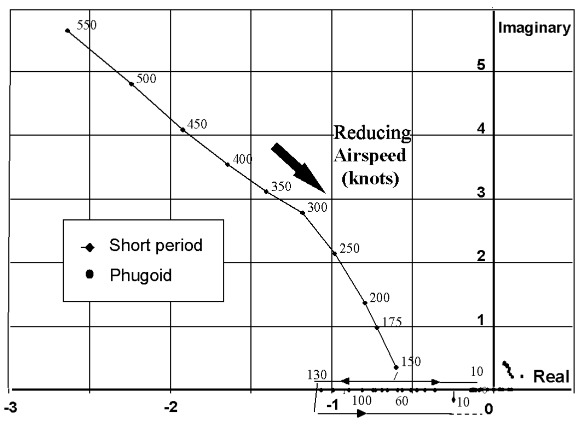

Figure 7: variation of typical STOVL aircraft longitudinal modes with airspeed

Figure 7 shows the loci of the longitudinal modes of a typical STOVL aircraft, as a function of its airspeed. The four eigenvalues of the unaugmented aircraft, i.e. the short-period and phugoid modes, move towards the origin as airspeed is reduced, that is, as dynamic pressure tends towards zero. The result is that the short-period mode's natural frequency reduces until the mode approaches the phugoid mode, close to the origin. At zero speed, if we assume that we have a control moment as an input (from the pitch reaction controls or any other device) then a transfer function of the type K/s^2 can be used to approximately represent the dynamics of the pitch attitude response. Similarly, the transfer function type K/s^4 can be used to approximate the aircraft's horizontal fore and aft position response. In practice, this is not achieved exactly, since there are still small damping terms due to jet-induced forces and moments. The result is four modes that are close to the origin, but which can be approximated as four integral terms - two associated with angular acceleration and two with translational acceleration.

The significant difference between an aircraft's longitudinal modes when it is in wing-borne flight and when it is jet-borne, is that in the former, the modes are largely de-coupled due to their significant frequency separation. This allows a reliable and accurate second-order short-period approximation to be made, and also permits the short-period response to be scheduled with long-period response variables such as airspeed, without adversely affecting the closed-loop stability of the short-period response.

In wing-borne flight, the short-period response is essentially a coupling of the pitching (θ) and heaving (w) motions, via changes in angle of attack, with the surging motion (u) being largely decoupled. For this case, u tends to be much larger than w, allowing approximations to be made, based on the assumption that u can be used in place of the total velocity (V). This situation changes completely in fully jet-borne flight, where it is the pitching and surging motions that are strongly coupled via changes in the aircraft's pitch attitude, with the heaving motion being largely decoupled. The approximate open-loop dynamics for a STOVL aircraft in the hover condition are as shown in the block diagram of Figure 8.

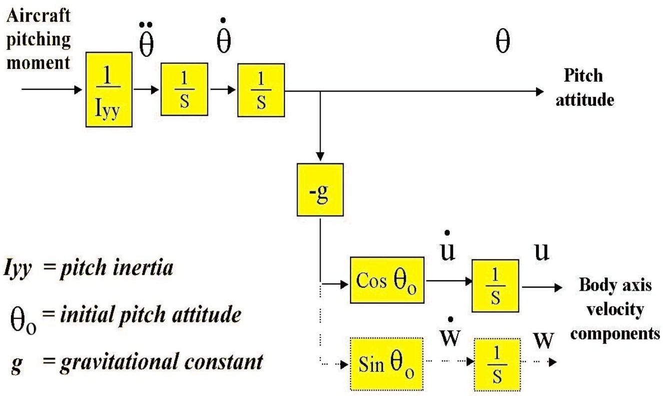

Figure 8: approximate longitudinal dynamics in the hover condition

In the transition region between wing-borne and jet-borne flight, the pitching, heaving and surging motions of the basic aircraft are all highly coupled and simple approximations cannot be made easily. Not surprisingly, this is also where the pilot's workload is likely to be highest and therefore, where automatic control, with response de-coupling, is highly desirable and has much to offer. As a result, it is also the region for which control law design for a STOVL aircraft is most challenging.

We will now consider how the basic aircraft modes can be augmented by the use of feedback within an integrated flight and propulsion control system, in order to provide satisfactory aircraft handling. Without the use of feedback, the aircraft may be flyable but could be difficult to control, and will probably exhibit a high pilot workload. A well-designed feedback system can be used to provide good handling qualities with a reduced pilot workload.

4.2 STOVL control laws

Besides the rigid body dynamics of the basic STOVL aircraft, many other dynamic modes (eigenvalues) arise due to its propulsion system, nozzle vectoring system, reaction control system and the airframe structure. Closed-loop systems introduce further modes due to the control law filters, the motion and air data sensor systems and their associated signal filtering, e.g. to attenuate the measured response of structural modes and the effects of digital aliasing on the feedback signals.

Figure 9 shows part of the pitch control laws structure for a STOVL aircraft. The main component is the thrust vector equations that convert the pilot's aircraft response commands into demands for the thrust vectoring system [8]. These non-linear functions aim to decouple the aircraft's longitudinal responses in jet-borne flight, such that three separate controllers can then be designed for pitch attitude, height rate and groundspeed control. Typically, well-conditioned proportional plus integral controllers might be used in these closed-loops, further increasing the decoupling by trimming out any errors between the commanded and actual aircraft responses. The controller designs are usually achieved by tuning time and frequency response characteristics, in order to provide satisfactory handling qualities and adequate control loop stability margins. In practice, perfect de-coupling cannot be achieved due to non-linearities and modelling inaccuracies, but the coupling can be minimised to a level where it is not considered to be significant.

4.3 Pitch attitude controller

If we consider a STOVL aircraft at low speed with a unit pitching moment, then its angular acceleration response can be approximated as being proportional to the reciprocal of its pitch inertia (see Figure 8). The associated pitch rate and attitude responses can be obtained by single and double integration of this acceleration response. The coupling of the pitching response into the aircraft's u and w body-axis velocity components is mainly via the change in the aircraft's pitch attitude and hence, the change in the resolution of the gravity vector along the aircraft's X and Z axes.

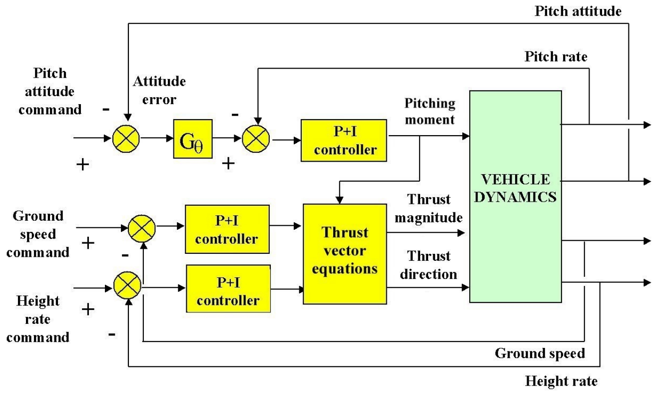

Figure 9: STOVL aircraft pitch control laws structure

Since the trimmed pitch attitude at low speed is likely to be small (say < 12 degrees), then the coupling with longitudinal speed will be large and the coupling into heave, significantly less. If we now consider the effect of designing a closed-loop attitude controller (Figure 10), the first step is to design a pitch rate inner loop to provide adequate damping of the open-loop integral modes. In this figure it is shown that increasing the feedback gain (Gq) eventually reduces the damping of the resulting complex pitch attitude mode; it is this that limits the bandwidth and achievable performance of the closed-loop system. The low frequency complex mode, that is derived from the double integrator in the inner loop, is the dominant mode in terms of the closed-loop pitch rate response. In practice, there will be many other modes at higher frequencies. Although these modes do not affect the loci significantly at low frequencies, they do have a significant impact on aircraft handling and stability margins, and must not be ignored when carrying out detailed design and flight clearance work.

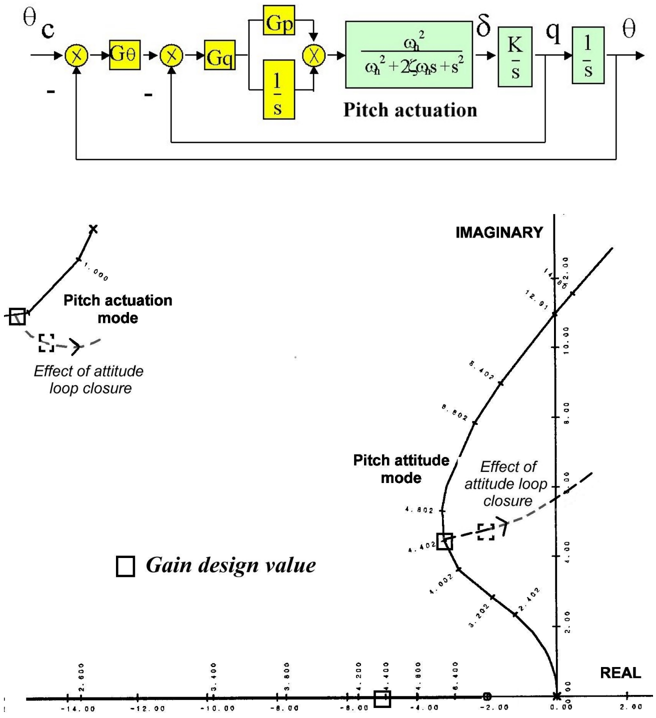

Figure 10: pitch attitude controller and root loci for pitch rate and attitude loop closures

Once a satisfactory inner loop design has been established, an outer, attitude control loop can be closed through a proportional gain. This feedback reduces the damping of both the dominant low frequency mode and the actuation mode, as shown in Figure 10. At this stage, some tuning of the gains might be required to obtain a deadbeat attitude response and satisfactory inner loop stability margins (e.g. 6 dB gain margin and 45 degrees phase margin).

With the thrust vector under manual control, the pilot might be given separate control levers for commanding its magnitude and direction, i.e. throttle and nozzle angle levers. However, in order to minimise pilot workload for future aircraft, a more automated approach is recommended. For the purposes of this paper, we will now consider the design of height rate and groundspeed control laws, although several other types are possible, such as those based on acceleration commands.

4.4 Height rate controller

For a unit change in thrust magnitude, the height acceleration response at low speed (say < 30 knots airspeed and with the nozzles forward) can be approximated, as the reciprocal of the aircraft's mass, as indicated in Figure 11. In closing the height rate control loop via a proportional plus integral controller, the basic aircraft's integral term combines with the controller's integrator to produce a dominant real mode as shown in the root locus diagram. The frequency of this mode increases with increasing controller gain GH, but is limited by the destabilising effect of this feedback on the powerplant mode. There are now four sets of significant closed-loop modes. The two pairs of complex modes from the pitch attitude controller should be largely unaffected by the closure of the height rate control loop, provided that the loops are adequately decoupled. In practice, a small amount of coupling is to be expected - even within the modelling environment.

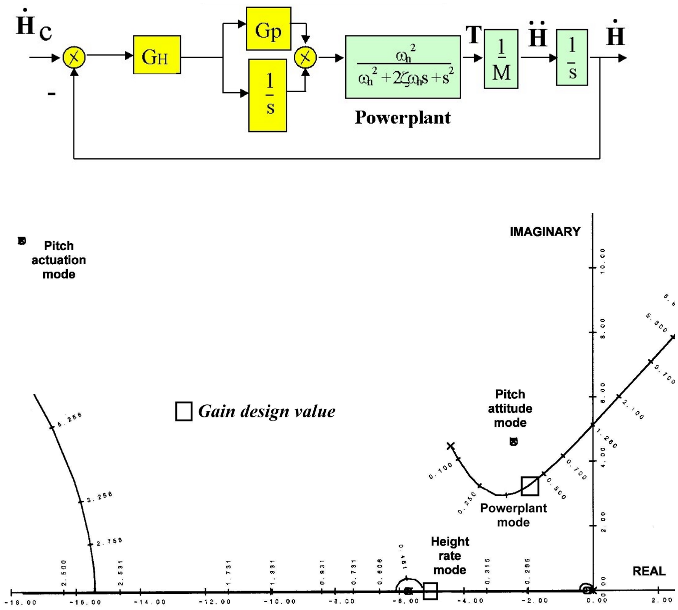

Figure 11: height rate controller and root loci for control loop closure

4.5 Groundspeed controller

Finally, a controller is now introduced around the remaining open-loop degree of freedom, to control the aircraft's groundspeed. This speed measurement is orthogonal to that used by the height rate controller, but its controller structure and design are very similar, as indicated in Figure 12. At low speed with the nozzles forward, the transfer function between the nozzle response and groundspeed can also be approximated by the integral of the reciprocal of the aircraft's mass. In closing the groundspeed control loop, a further dominant real mode is introduced, from the combined integral terms. The nozzle actuation mode damping provides the limit on the bandwidth of the design. Once again, the modes introduced by earlier loop closures remain essentially unchanged (hence the pole-zero cancellations), if the loops are adequately decoupled. There are now six sets of significant 'rigid aircraft' closed-loop modes: pitch attitude, pitch actuation, height rate, powerplant, groundspeed and nozzle actuation.

It is not intended to take this any further in this paper. Although the discussion has concentrated on the longitudinal axes, most of what has been described can be read across to the lateral/directional axes - if lateral thrust vectoring were to be available. The descriptions above, although only indicative in nature, will hopefully have increased the reader's understanding of the longitudinal dynamics of both CTOL and STOVL aircraft, from a stability augmentation point of view. There will be many eigenvalues in the closed-loop system and irrespective of the modelling environment and design techniques used, it should always be possible to trace each eigenvalue back to its physical and functional components within the non-linear model. This is important in order to gain an understanding of the design, to determine how it is influenced by the hardware dynamics and to know how to fix it if it goes wrong!

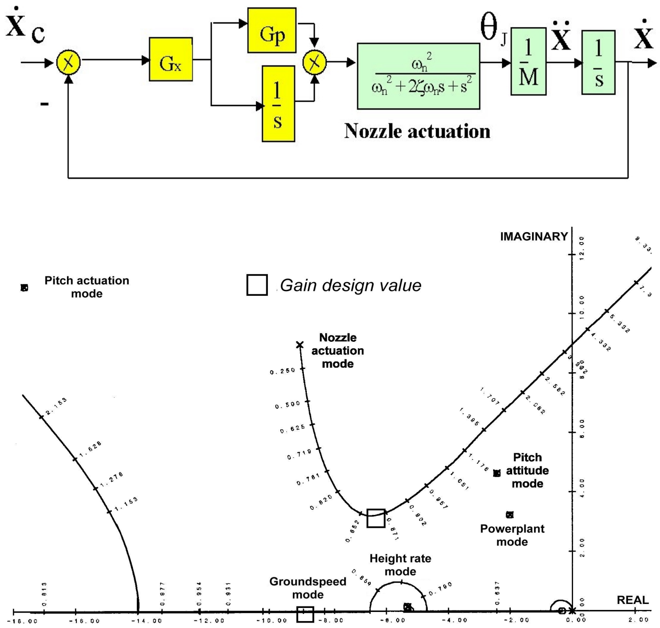

Figure 12: groundspeed controller and root loci for loop closure

5 Implications for STOVL aircraft design

This paper has described how STOVL aircraft can have many eigenvalues within their closed-loop system, especially if a high degree of control augmentation has been introduced. An implication of this large number of modes is that the CTOL handling qualities requirements that are used for wing-borne flight (e.g. those for short-period frequency and damping), are unlikely to be relevant for jet-borne flight. It might be necessary to consider criteria that address each of the response modes separately. STOVL handling qualities criteria development is an area where further research is needed. Existing design specifications, such as MIL-F-83300 (1970) and AGARD R-577 (1973), do not provide sufficient guidance and therefore, from the late 1970s onwards, there has been a lack of design aims and design criteria for advanced control laws for STOVL aircraft. Criteria have subsequently been developed and partially validated within BAE SYSTEMS, to provide a guide for the design of

STOVL flight control systems. These criteria define handling qualities metrics for control laws design at low speed and in the hover.

Following the introduction of feedback into a system, it is important that the aircraft's closed-loop response characteristics and hence its handling qualities, are satisfactory. When using the powerplant for short-period control within a closed-loop system, a specification of the required response dynamics becomes an important design driver, in order to make it possible for a suitable design to be achieved. In many ways, the propulsion system can be regarded as a special case of an actuation system, with a high degree of complexity. This gives a new dimension to the required propulsion system performance specification, which is traditionally defined in terms of achievable static thrust characteristics. Decoupled engine responses, thrust bandwidth and response linearity become important considerations for both the powerplant and control law designer. It should be possible to derive an initial specification of the required powerplant dynamics, from the handling qualities requirements, by carrying out simple designs and trade studies. This is another area where further work will be required in the future.

A final implication, due to the complexity of STOVL flight control, is that complex models will be produced, leading to complex results. The design and flight clearance tools will need to be capable of managing this complexity and must provide accurate and reliable results. It is equally important that the designer can correctly interpret these results and make sound decisions regarding the performance, robustness and safety of his design. The performance aspects in the time domain are usually very visible and relatively easy to interpret and understand. However, in order to gain a similar level of understanding of robustness in the frequency domain, an eigenvalue analysis as described in this paper, is an essential first step towards establishing such an understanding.

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