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Generic regional aircraft flying qualities for the approach and landing task

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Chapter 1

Introduction

Many changes have occurred in the past 20 years in aircraft manufacture and development. New technologies have appeared, spanning the entire aircraft design environment, such as new production methods, new materials and new avionics systems. These new methods have been developed for two reasons. For military aircraft, they have arisen through the need to improve performance. However, for civil aircraft they have arisen through the need to reduce the overall cost.

This report considers one aspect of these technologies for civil aircraft: fly-by-wire. This technology uses electrical signalling in place of conventional heavy mechanical control runs. In addition, fly-by-wire generally permits improvements to be made in aircraft flying and handling qualities. This requirement has originated from two main sources; a need to make improvements in the light of an increasing amount of experience, and a requirement to cope with aerodynamic modifications which have been implemented to improve aerodynamic efficiency, but which have a deleterious effect on the aircraft's flying and handling qualities. Both of these adverse effects have come about from a desire to reduce costs for the end aircraft user, i.e. the airlines.

The aircraft used for these evaluations is a Generic Regional Aircraft, of about 100 seats and a weight of 90,000 lbs. Only a limited portion of the flight envelope was considered since these evaluations primarily concentrate on the approach and landing flight phase.

These evaluations are being carried out as part of a joint Avro International Aerospace – Cranfield University Engineering Doctorate programme researching advanced flight control system design for a Generic Regional Aircraft. The overall aim of this programme is to produce a control law design which gives aircraft in question excellent handling qualities. The evaluations described here comprise the first in a series of three planned studies, and consider solely the approach and landing flight phase.

1.1 Handling and Flying Qualities

This report primarily considers handling and flying qualities for the Generic Regional Aircraft. Handling qualities describe the airframe / flight control system response characteristics. Flying qualities are considered to be slightly different since the task and other relevant factors such as cockpit display design are considered.

The definition of good handling and flying qualities is not easy to make as both encompass many aspects of aircraft design and operation. However, Ashkenas [1] describes the following qualities which are often associated with good aircraft flying and handling qualities.

1. Trim and unattended operation - the pilot must be able to trim the aircraft so that it will fly "hands off".
2. Large amplitude manoeuvres - the pilot must be able to perform or control large amplitude manoeuvres from given cues.
3. Regulation and precision flying - In closed loop control, the pilot must be able to hold the aircraft on a desired trajectory in the presence of disturbances, such as gusts.

All of the elements of the pilot - aircraft closed loop system need to be considered [2]. This is because the effects of display design and other pilot-machine interfaces have a large effect on the aircraft's flying qualities. This includes the effects of inceptor characteristics, such as whether a sidestick or centre control wheel is used. For these evaluations, only a centre control wheel is used. Other aspects of information flow such as display design and pilot to pilot communication are briefly considered.

The primary driver behind flight control system design is to obtain the best performance out of the pilot - aircraft combination. Therefore the aircraft and its associated system should be designed around the pilot, which is known as 'human centred design'. Pilot situational awareness, or the way in which the aircraft conveys information to the pilot is also of crucial importance and this is also considered in this report.

External disturbances such as atmospheric effects and Air Traffic Control (ATC) requests also need to be considered, as recommended by Field [2]. The reasons for this are that gusts can have a pronounced effect on the perceived aircraft handling and flying qualities, and can drastically modify the pilot ratings. In addition, there are many constraints placed on aircraft by ATC, and a control law which prevents the aircraft from achieving these requirements is obviously not suited to the task which it is required to accomplish. However, these external disturbances have been ignored for these evaluations as they may initially obscure the underlying characteristics being evaluated, and it is planned to consider them in a subsequent set of evaluations.

1.2 Initial research

Much of the initial handling qualities research originated for military fighter aircraft from the desire to improve aircraft performance, and thus gain superiority over the opposition. The technologies which were being used to produce modern flight control systems were still expensive though, and had yet to evolve to the civil aircraft manufacturers. Therefore little work was initially done on civil aircraft handling qualities; the majority was performed for military aircraft, primarily fighters.

As the technologies matured, they started to find application to modern civil aircraft. Also, the drive to improve flight safety made the civil aircraft manufacturers take note and to start looking at handling and flying qualities more seriously. Therefore more research programmes aimed at transport aircraft (both civil and military) were carried out, which greatly expanded the limited information database. However, much of the data is still only applicable to fighter aircraft, and therefore must be treated with caution when considering large civil aircraft.

The piloting tasks for civil and military aircraft may be drastically different. With fighter aircraft, a large number of the handling qualities investigations concentrated on pitch pointing tasks, which are relevant to the majority of the weapon aiming and in-flight refuelling tasks. However, civil aircraft handling qualities investigations have tended to concentrate on the approach and landing task, since this is considered to be the most critical piloted flight phase for a civil aircraft. This is a substantially different task to a pitch pointing one, and necessitates a different set of requirements.

Many different control laws have been evaluated over the past 30 years in a variety of variable stability aircraft and in-flight simulators. These have evaluated literally thousands of response types. Since it is obviously impractical to evaluate every one of these for the current programme, some initial selection was performed.

1.3 Previous Work

As previously stated, the aircraft under consideration here is a Generic Regional Aircraft. Previously, work has been performed at Cranfield [2] on this type of aircraft, again looking at the approach and landing phases. This programme considered command concepts and their applicability to the same Generic Regional Aircraft. Field isolated some of the key characteristics which are relevant to the approach and landing task for a variety of command types. This report builds on that work by applying those 'key concepts' to control laws which are implemented in actual aircraft.

The control laws being evaluated for this study are based on control laws which have been implemented on existing fly-by-wire aircraft. This follows on from Field's work [2], which considered generic command concepts for a Generic Regional Aircraft. Therefore, as well as current control law types, additional laws will be evaluated which follow on directly from the current laws in use and the results of Field's work.

From his work, it is clear that there are fly-by-wire control strategies where follow-on studies would be beneficial. Hence it is also proposed, for example, that the issue of speed stability in the approach flight phase be considered after the initial evaluation work. The scope of the programme will be determined from the results of an initial review, together with the final conclusions from Field.

The control laws designed are representative of actual control laws used in practice. This implies that the control law structure will be representative, of actual flight control systems, but excluding features such as structural filters. Also, limits are placed on the sensing requirements, and only commonly available signals are used. A notional flight control system hardware architecture is available for this aircraft [3], and this is considered when the control law architecture is designed.

Angle-based control laws such as pitch attitude command or flight path angle command (but with the exception of angle of attack) will not be evaluated. They can give good qualities for a given trim point, but they have high trimming requirements associated with them, which goes against the requirement for minimal trim changes for flight path change. Field [2] found that angle command laws were rated worse than the corresponding rate command law for the approach task. Also, they are not currently used in practice as the principal command concept for any aircraft, with the exception that they are generally used in the flare to give conventional characteristics, as previous studies have shown.

The importance of the long term response of the aircraft is also considered for these evaluations. Speed control has been assessed by considering the effects of an autothrottle. An artificial long term mode can be introduced by feeding speed error back to the pilot's demand. This was assessed for the laws in question here.

During the design process, the effect of higher order systems and alternative response types need to be considered since a particular criterion which may be valid for one command concept and flight phase may not be valid for another. This is another conclusion from Field's work [2], and is also considered by French [4] in the form of Mission Oriented Flying Qualities (MOFQ). French makes the point about task tailoring, in that an aircraft's handling qualities must be tailored to the task which the aircraft is being used for. Task tailoring is also a strong theme throughout Field [2]. Therefore the flying qualities evaluations are broken down into distinct phases so that the suitability of each law to each phase may be considered.

1.4 Objectives

The study is designed to compare the handling qualities of the current fly-by-wire transport aircraft, in order to provide the following information.

1. To compare the current control law concepts in order to assess whether any one particular concept is more suitable than the remainder for the approach and landing task.
2. To provide information concerning the design of the control laws with respect to the currently available literature to assist in the design process for control laws of this type in the future.
3. To provide a database of information concerning pilot workload for different control law concepts.
4. To validate the current handling and flying qualities criteria for aircraft handling qualities in the longitudinal axis.
5. To assess the effects of speed stability and the autothrottle on the flying and handling qualities of the aircraft.

This will be done using a total of 10 augmented control laws plus the baseline aircraft. The control laws are based on laws in current use, or derivatives of them, and have been designed to a series of law-independent requirements. Effects due to changes in the position of the aircraft centre of gravity have been ignored for these evaluations. Since the control laws can be designed to cope with this in a way which is transparent to the pilot. Changes in aircraft mass have been ignored for the same reasons. Lateral and directional control laws have not been explicitly considered. The reason for this is that the majority of fly-by-wire aircraft utilise the same lateral control law strategy, and this has been adopted for this aircraft. An existing lateral law for the aircraft under question was therefore used.

The following ten control laws will be considered.

1. Augmented Aircraft (i.e. angle of attack command law)
2. Pitch Rate (q)
3. Pitch rate with speed feedback (qU)
4. C* (i.e. Pitch Rate + Normal Acceleration blend)
5. C* with speed feedback (C*U)
6. Normal acceleration (Nz)
7. Normal acceleration with speed feedback (NzU)
8. Pitch rate with angle of attack feedback (qα)
9. C* with angle of attack feedback (C*α)
10. Normal acceleration with angle of attack feedback (Nzα)

For the purposes of these evaluations, the configurations will be assessed using the following methods, for the reconfiguration, approach and landing tasks.

1. Pilot comment cards
2. Cooper Harper ratings
3. Workload measurements

In addition, qualitative performance data will be measured such as the aircraft touchdown position and velocity. Also, desirable and adequate performance levels will be defined for the task and aircraft considered. The discussion of considerations which are required for this is within this report.

Finally, this report considers the design criteria which are used during the design process. It is important, from an application point-of-view to be able to repeat the design at the numerous flight cases which need to be considered during the design phase for a fly-by-wire aircraft, and therefore the process which is used to achieve the final design is considered.

1.5 Report Structure

This report is structured in the following way.

Chapter 1 introduces the evaluation series, and gives some background behind the work.

Chapter 2 considers some of the relevant background and theory.

Chapter 3 considers the control law design.

Chapter 4 describes the aircraft under consideration in more detail.

Chapter 5 describes the experiment design.

Chapter 6 gives the experimental results for the study.

Chapter 7 gives the discussion of the results.

Chapter 8 states the conclusions.

Appendix A contains the step response plots for the individual laws.

Appendix B contains control law and autothrottle gain schedules.

Appendix C contains the response plots.

Appendix D contains the comment cards used.

Appendix E contains the actual pilot comment card.

Note that Appendices A to E are contained within volume 2.

Chapter 2

Background and Theory

2.1 Flying and Handling Qualities Criteria Discussions

In order to be able to design and assess the flying and handling qualities of aircraft, criteria have been developed to make this task easier. However the use of such criteria is not as simple as it may initially seem. Due to the fact that the criteria are essentially based on experimental data, they are only relevant in the context in which the data was obtained, and must therefore be treated accordingly. This chapter briefly describes the criteria which have been deemed to be useful, and also considers their validity for the evaluations considered here.

Much has been written on criteria and their comparison. Therefore the number of criteria considered will be limited to those deemed relevant. For a fuller explanation of other criteria which have also been considered, see reference [5] for longitudinal criteria and [6] for lateral criteria.

2.1.1 Neal-Smith

This section covers the Neal-Smith criterion, which was initially developed for class IV aircraft, and then the modification made to this criterion for class III (transport) aircraft.

Description

Neal-Smith is essentially a pilot modelling task. It works by calculating the required pilot gain and phase to place a specified aircraft - pilot transfer function phase angle at a given frequency, known as the Neal-Smith bandwidth frequency, and is different to the frequency used by the Bandwidth criterion. This is done through the use of a pilot model transfer function.

$$P_{PC} = K_P \frac{(\tau_{p1}s + 1)}{(\tau_{p2}s + 1)}_{\omega_{BW_{MIN}}} \tag{2.1}$$

The parameters K_P, τ_{p1} and τ_{p2} can be determined from the required pilot lead / lag and gain compensation requirements. Pilot opinion is then correlated with these parameters to validate the criterion. Neal-Smith is based around the following assumptions [7] :

1. PIO tendencies. It seems straightforward to relate PIO tendencies to the closed loop resonance $|\theta/\theta_c|_{MAX}$.
2. Pilot compensation. It seems reasonable that a pilot's comments concerning his compensation are closely related as to whether he has to generate phase lead or lag (over and above his 0.3s delay). Since the phase characteristics are important in the vicinity of the bandwidth, it seems logical to describe the pilot's phase compensation in terms of the following phase angle:

$$P_{PC} = K_P \frac{(\tau_{p1}s + 1)}{(\tau_{p2}s + 1)}_{\omega_{BW_{MIN}}} \tag{2.2}$$

   This phase angle can be determined from the values used, and will be positive for lead compensation, negative for lag compensation. Hence, when the pilot states that he has to overdrive the aircraft, it will probably be positive, and when he states that he has to fly it smoothly, it will probably be negative.
3. Stick forces. Pilots often comment on the steady stick forces, as well as the forces required for tracking. Here, steady stick forces relate to the stick forces per g. In selecting the elevator to stick gearing, the pilots insisted on a gearing that allowed large load factors with a reasonably steady pull. This often caused initial forces, which are probably related to pilot gain, to be compromised.

Good configurations exhibit essentially constant closed loop performance for a relatively wide range of bandwidths. Bad configurations exhibit large changes in closed loop performance for small changes in bandwidth, known as a flying qualities cliff. The Neal-Smith criterion is generally a good discriminator, except for low short period damping, where the phase compensation becomes very dependent on the bandwidth levels chosen, especially for poor configurations. Much work has been done to extend Neal-Smith.

The level 1 Neal-Smith boundaries for the approach can be found on figure 2.1. The original boundaries were devised by Neal and Smith [8], and the revised boundaries were developed by Smith [9], using a different bandwidth frequency (3 rad s^{-1} in place of the original 3.5 rad s^{-1}). A typical pilot time delay used is 0.2 seconds.

Modified Neal-Smith Criterion

The modified Neal-Smith criterion for transport aircraft is defined by Mooij as

> For the final approach and landing phases of the mission of a transport aircraft, acceptable dynamic characteristics of the pilot/aircraft closed loop system for pitch-attitude control are required.

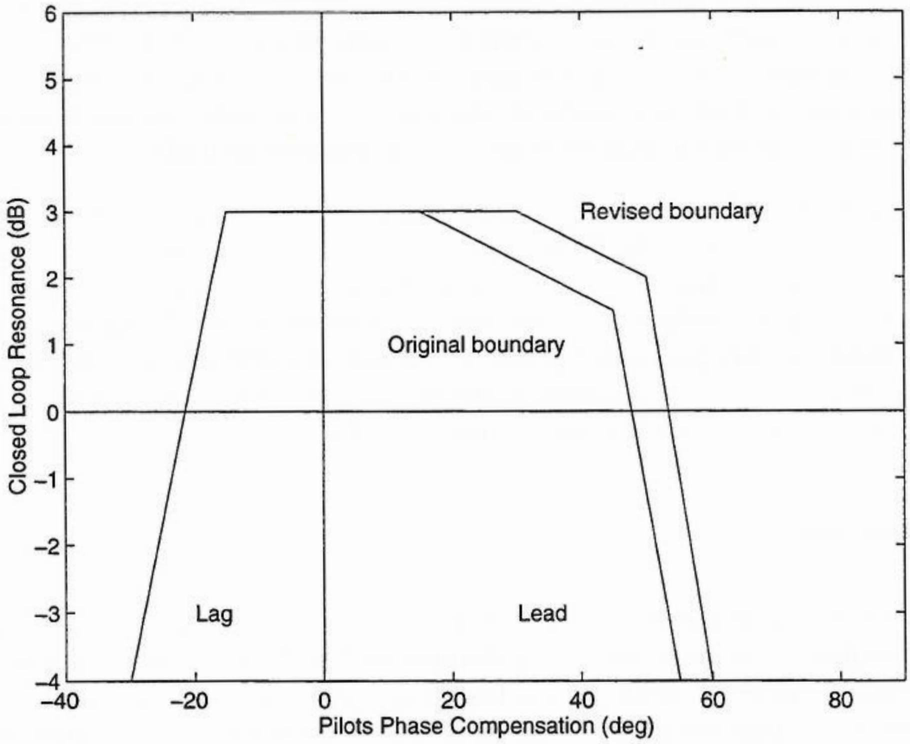

Figure 2.1: Neal-Smith Boundaries for Level 1 flight, Cat C, Class III

It was developed by Mooij [10] in order to account for deficiencies in the Neal-Smith criterion when applied to transport aircraft, following experiences using the NLR ground based simulator and the USAF TIFS, which involved flying a medium weight transport aircraft through an ILS approach to touchdown.

The basic principles behind this modified criterion are the same as the original Neal-Smith criterion, where the pilot's comments concerning his compensation are closely related to whether he has to provide phase lead or phase lag. Phase characteristics are most important in the region around the bandwidth frequency, and this causes the majority of the problems with the conventional Neal-Smith boundaries as they are suited to a class IV fighter and not a class III transport aircraft. Therefore Mooij proposes a new bandwidth, and revises the previous Neal-Smith boundaries to account for the difference in aircraft class.

Three aspects were considered :

1. The selection of the appropriate time delay
2. The selection of the Bandwidth for the Neal-Smith analysis
3. The determination of maximum resonance.

Mooij found that a 0.3 second time delay was appropriate for the criterion. He also found the variation in compensation with different pilot bandwidths (1.2, 1.4 and 1.6 rad s^{-1}) and with good configurations was low. The pilot compensation required for the two larger bandwidths expressed in terms of lead time constant was found to exceed 1 second, which was considered to be the limit for level 1 qualities. Hence 1.2 rad s^{-1} was chosen as the minimum required bandwidth. The revised boundaries modified the original boundaries (see figure 2.1) by reducing the maximum phase lead to 50 degrees, and reducing the maximum closed loop response to 0 dB.

The only provision for this criteria is that the resonance will need to be recalculated for values of minimum bandwidth that differ from 1.2 rad s^{-1}. An appreciable variation in resonance is considered to be an indication that the dynamic characteristics of the pilot/aircraft closed loop system for the particular configuration are strongly dependent on piloting technique. This may indicate that handling qualities problems may be present and application of the criterion may give unsatisfactory results. The new assumed bandwidth is 1.2 rad s^{-1}, but higher and lower valuers need to be considered to account for pilot technique differences [11].

2.1.2 Bandwidth

This was developed by Mitchell and Hoh of Systems Technology Inc. as a simple method to assess the suitability of the open loop pitch attitude to stick force transfer function. The criterion attempts to define a range of pitch control frequencies over which the aircraft has good response characteristics. It is a task orientated criterion which is applicable to highly augmented aircraft.

This criterion is made up of two requirements, pertaining to both equivalent time delay (to account for higher order dynamics) and the bandwidth of the aircraft transfer function (e.g. pitch attitude response to stick force transfer function). The equivalent time delay and phase delay are then used to determine the level characteristic of the aircraft.

The bandwidth criterion is task and class orientated, and therefore for it to be valid the appropriate bandwidth must be chosen. Bandwidth is an application of the crossover model, the concept of which is that a human can be treated as an element of a closed loop system for compensatory tracking tasks. It is defined as the frequency where there is 6 dB or 45 deg gain or phase margin from ω_{-180}, or the frequency where the phase is -180 degrees. The 6 dB value comes from experience - a lesser value tends to give a PIO prone aeroplane. The selection of a 45 degrees phase margin is where the task requires full attention, but less than that required for maximum effort [12]. However, the boundaries are still somewhat arbitrary. Look in the following reference for information concerning new tasks and aircraft categories. [13] The boundaries are shown in figures 2.2 and 2.3.

It was found by Weingarten and Chalk [14] that closed loop pitch attitude bandwidth requirements for civil transport aircraft are less than for fighters, with a value of 1.5 rad s^{-1} for the approach task. It was found that the evaluation pilots applied a less rigorous standard to the approaches because the configurations evaluated were defined as large and heavy aircraft, and therefore able to accept longer time delays. However, according to Berthe, Chalk and Sarrafian [15], bandwidth does not provide an adequate flying qualities prediction when based on pitch attitude.

The upper bandwidth limit tends to be defined by stability boundaries [12]. Bandwidth itself describes the ability of a pilot to follow a range of input frequencies with the bandwidth being related to the highest frequency that the pilot can follow.

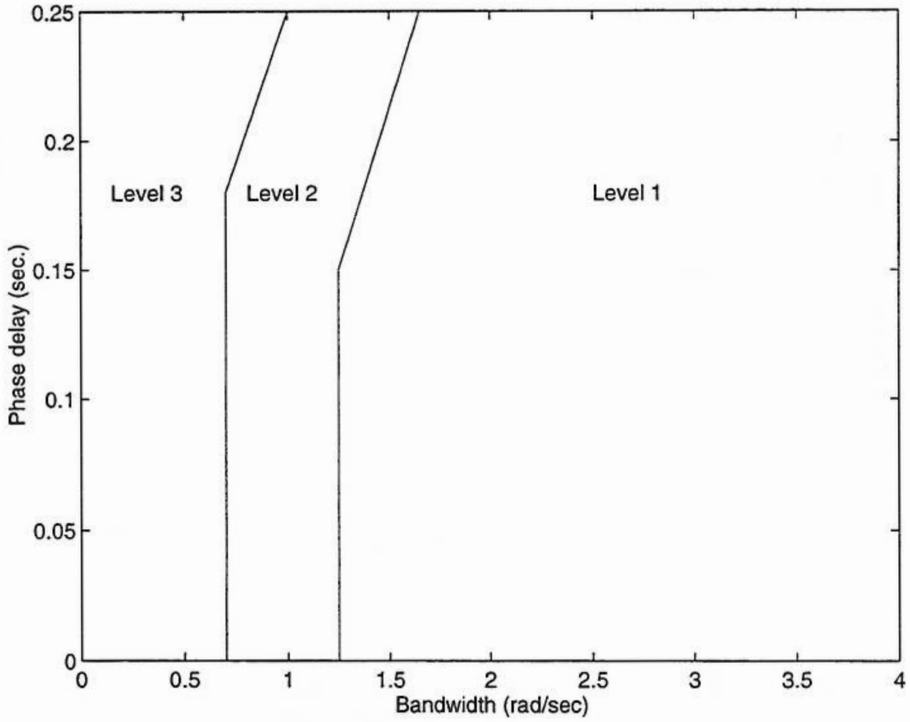

Figure 2.2: Pitch Attitude Bandwidth versus Phase Rate Boundaries

Bandwidth is very dependent on the short period natural frequency (for a conventional aircraft), or the short term mode (for a non-conventional aircraft) and therefore any limit implied on the short term mode frequency would imply a limit on the configuration bandwidth.

Efforts to develop bandwidth showed that the pilot is sensitive to the shape of the phase curve at frequencies beyond the bandwidth frequency. This is defined by the phase delay parameter. Physically, phase delay is a measure of how a pilot behaves as he tightens up his crossover frequency, i.e. tries to control the aircraft beyond the bandwidth frequency. Large values of phase delay indicate that there is a small margin between normal tracking at 45 degrees phase margin and instability. A PIO-prone aircraft is often said to have a high phase delay.

Phase delay is typically close to the equivalent systems time delay. A value of equivalent time delay greater than 0.1 seconds was shown to give a worsening of a CHR by one point. The only factor which explains this, according to Hoh [12], is the steepening of the phase slope above the bandwidth frequency and not because of the time delay introduced since the time delays are typically very small, i.e. 0.1 to 0.2 seconds. It is difficult to measure time delay since it is sensitive to a lot of different parameters, which can contribute to experimental error. Since phase delay is calculated from a frequency-weighted slope, i.e the value of phase delay will be higher for a lower ω_{-180} frequency. Therefore phase delay is more critical when the ω_{-180} frequency is low rather than at the piloted crossover region [2].

In addition, French [4] states that phase above ω_{-180} degrees can be attributed to equivalent time delay since in a conventional unaugmented aircraft response, the pitch attitude phase response

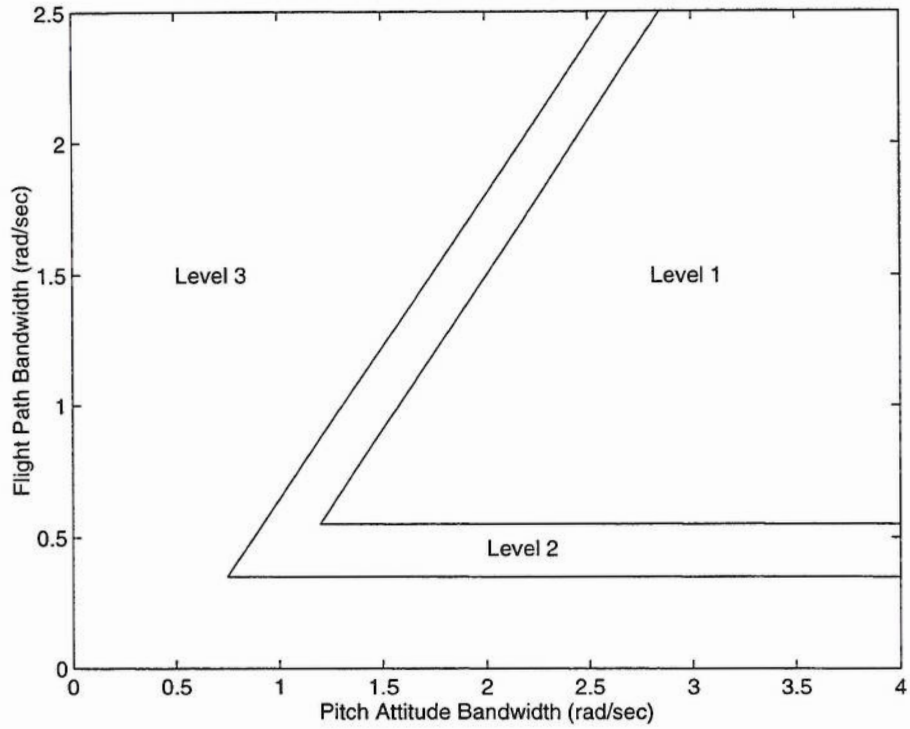

Figure 2.3: Pitch Attitude Bandwidth versus Flight Path Bandwidth Boundaries

does not go below -180 degrees. Phase delay is an approximation to equivalent time delay, and therefore an approximation to the phase slope at phase angles above -180 degrees. Accordingly the problem with phase delay is it characterises the slope of the phase curve for frequencies above -180 degrees, whereas the critical part of the slope is the part of the slope approaching and just after -180 degrees. Here, the suitability of the parameter is questioned. Though the bandwidth criterion is generally sound in its basic approach [4], the suitability of parameters chosen to characterise the open loop frequency response are questioned. While proposed changes to the limits on phase delay will make the criterion more credible, the use of bandwidth as a correlation parameter appears ill-suited and overlooks the simpler and probably more appropriate use of phase crossover frequency. Therefore French recommends redefining the bandwidth criterion to use the phase rate correlation parameters.

Bandwidth is applicable to tasks which require closed loop compensatory tracking. Such tasks involve small amplitude attitude changes. In-flight and ground simulation has shown that the bandwidth requirement decreases as the amplitude of the manoeuvre increases. therefore the mission orientated flying qualities must account for this. For very large amplitude manoeuvres, the pilot operates open loop. An increased bandwidth is required for divided attention tasks, a degraded usable cue environment (i.e. worse visual conditions), and a target acquisition and tracking task [13].

Response characteristics

This section highlights some of the terminology used when expressing response characteristics. Generally, K, K/s and K/s^2 response characteristics are referred to.

A K response is where the output is directly proportional to the input for a given transfer function. In this case, there will be no phase loss, and the magnitude of the output to the input will be determined by the magnitude of K.

A K/s response is where the relationship between the output and input has integrator-like properties. Therefore a step input will produce a steadily increasing output. The rate of increase is determined by the magnitude of K. On a bode plot, this corresponds to a magnitude gradient of -20 dB/Dec, and a phase of -90 degrees over all frequencies.

A pure K/s^2 response in a particular parameter is where that parameter will increase with a constant acceleration to a step input. This effectively the same as having two transfer function poles at the s-plane origin (or two free integrators), and therefore low frequency phase of -180 degrees. For the actual transfer function, there may be K/s^2 properties between certain frequencies, depending on the location of the poles and zeros. These regions are characterised by a decreasing bode plot gain of -40 dB/Dec, and approximate phase of -180 degrees. This has the effect of dramatically reducing the gain and phase as soon as the K/s^2 region is entered, and therefore the bandwidth is effectively constrained by this.

The Application of Bandwidth

While good attitude control is essential for closed loop manual flight, so too is flight path control, particularly for the landing approach. The bandwidth criterion accounts for this through its criteria on attitude and flight path bandwidths. Extended regions of K/s^2 (see section 2.1.2) in the flight path response result in loss of phase, which is visible in ω_{BW_γ} [2].

Hoh [12] states that a flight path bandwidth of less than 0.6 rad s^{-1} is a good indicator of poor flying qualities in the flare. Poor flight path can be improved to some extent by increasing the pitch rate overshoot and reducing the attitude dropback. Use of Direct Lift Control (DLC) can increase the flight path bandwidth, but it can be overdone, resulting in too much flight path response, and complaints from pilots. Therefore an upper boundary has been used. The upper boundary appears to be motion-induced, evident from in-flight simulators and is not apparent from fixed-base simulators [2]. The current bandwidth limits for civil transport aircraft will be shown later, along with the bandwidths for the configurations discussed.

Field [2] also found that when the pitch attitude bandwidth for rate command configurations was greater than 3 rad s^{-1}, the configurations were too abrupt. Field suggested that this implies that there is an upper limit on bandwidth based on sensitivity. Here, the highest bandwidth permissible has a specified sensitivity, and any sensitivity above or below this results in deterioration in pilot rating due to sensitivity problems. As the bandwidth reduces to the lowest value, the upper and lower sensitivity limits progressively separate, until the greatest available pitch sensitivity is obtained at the lowest permissible bandwidth frequency. For the attitude command systems tested by Field, the maximum attitude bandwidth is approximately 3 rad s^{-1}, while for the flight path command systems, the maximum pitch attitude bandwidth is approximately 4.5 rad s^{-1}. Field suggests that it is possible to extend this work to cope with alternate response types, although the data is not currently available to do this.

Weingarten and Chalk [14], performed an analysis which demonstrated that the pilot could achieve a higher bandwidth when seated well forward of the centre of gravity. It hints that an attitude bandwidth of 0.5 rad s^{-1} may be required, which correlates well with a NLR study showing 0.55 rad s^{-1}. French [4] questions the use of bandwidth, and suggests that crossover frequency might be more appropriate to use compared with bandwidth since it has a direct bearing on aircraft stability.

Gibson, [16] states that for a sufficiently forward cockpit, a limitation is exposed with bandwidth since the phase lag is always less than -135 degrees, and a phase angle bandwidth cannot be defined. This is not realistic, and results from the over-simplifying assumption of equating an artificial 'open loop phase margin' with a closed loop crossover frequency.

2.1.3 Control Anticipation Parameter and Low Order Equivalent Systems

The Control Anticipation Parameter (CAP) and Low Order Equivalent Systems (LOES) have been considered together since they are complementary, and strictly speaking, LOES is not a criterion. CAP's origin is a measure of the predictability of flight path control [16]. The initial rotational pitch acceleration is due to the angle of attack, the parameter mainly defined by the short period mode, which leads directly to normal acceleration and the corresponding flight path changes. Attitude is a continual summation of the angle of attack and the flight path angle.

The initial pitch rate is initially formed by the angle of attack rate since flight path is more or less constant. A lack of initial angle of attack response can cause poor landing flight path control, as found with the space shuttle. The corresponding sluggish normal acceleration growth corresponds to sluggish flight path control.

When the attitude dropback is zero, the pitch attitude response forms a pure K/s relationship (see section 2.1.2) after the initial pitch rate transient is complete. This is significant in the closed loop attitude tracking task. Also, a shorter flight path delay increases the dropback, and vice-versa. These result from changing the short period mode parameters for a classical response type.

LOES is a low order mathematical model which matches the high order model response. Equivalent parameters have been widely used for comparison and correlation of the flying qualities of high order dynamics for CTOL and V/STOL aircraft. Where possible, the equivalent systems parameters are compared with suitably modified modal requirements, which gives reasonable prediction of flying qualities.

Classical LOES uses an equivalent system representation to match the actual pitch rate frequency response to a simplified frequency response over a defined frequency range, by varying parameters on the simplified response. This therefore approximates the response of a high order aircraft to that of a 2 degree of freedom one, coupled with a time delay, which partly represents the high order effects. Bounds are placed on the match between the high order system (HOS) response and the

LOES approximation. These have been determined from reference [17], which determined what variation the pilot could tolerate without modifying his rating of the configuration by a set limit.

LOES should not be used when there are high order dynamics in the region of piloted crossover (0.7 - 4 rad s^{-1}) due to problems in matching the response and should not be used for non-conventional aircraft dynamics [12], such as a non-conventional pitch attitude or flight path response characteristic, or high order dynamics in the crossover region.

CAP can be shown to be proportional to manoeuvre margin and stick force per G for unaugmented aircraft [5]. It can be interpreted in the following ways

1. The initial and final responses must be neither too sensitive or insensitive to commanded flight changes.
2. As a measure of initial pitch acceleration per pound of stick force (classical definition of stick sensitivity) times stick force per G.
3. As a measure of frequency separation between the flight path response ($1/T_{\theta_2}$) and the pitch response (ω_{sp})

MIL-STD-1797A [18] requires a simultaneous match of the normal acceleration to pitch input and pitch rate to pitch input. This ensures that the value of $1/T_{\theta_2}$ remains reasonable. There is some discussion whether an acceptable match can be obtained with $1/T_{\theta_2}$ fixed, and the experts in the field are not agreed on this fact [12].

Blagg [5] also cites a modification made to CAP by A'Harrah and Woodcock [19] which includes the pilot's moment arm in the normal acceleration equation. This is due to the interpretation of CAP which states that it is the ratio of initial pitch acceleration to steady state normal acceleration, which defines the compatibility of the flight path response to the initial sensation of a pitch control input.

The equivalent short term mode frequency calculated using LOES can be used for the CAP assessment. In addition to this, the value of the equivalent short term mode damping ratio is calculated using LOES, and must be within defined limits (i.e. 0.35 and 1.3). Finally the equivalent time delay is calculated, and must be less than a specified value.

According to Hoh [12], CAP is a measure of the frequency separation between the short period frequency (ω_{SP}) and the flight path response ($1/T_{\theta_2}$), i.e. the size of the shelf, which is, in fact, related to the amount of pitch attitude dropback, see section 2.1.5. A frequency representation of the shelf, taken from Gibson [16] can be seen on figure 2.4. CAP is strictly proportional to this shelf distance multiplied by the short period frequency.

Therefore for a given CAP value, a Pilot flying an aircraft with a slower short period frequency should be able to withstand a larger amount of dropback. This seems to have been qualified by Mooij's work [10], as the pilots evaluating the class III aircraft under consideration could tolerate more dropback than the limits commonly published for fighter aircraft.

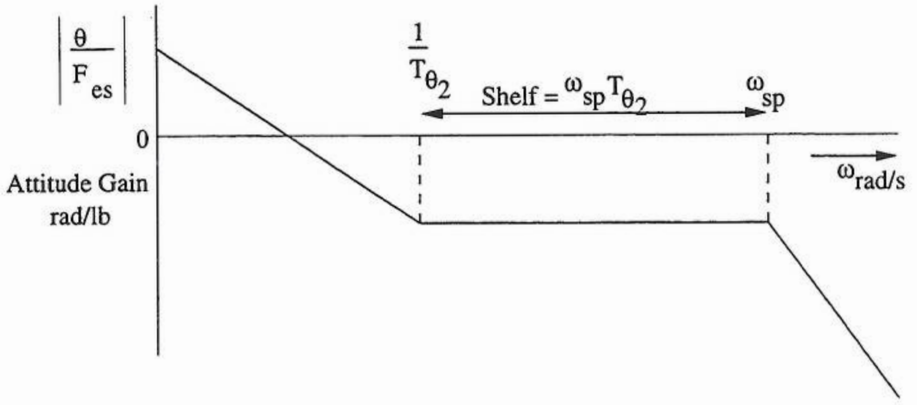

Figure 2.4: Short period / lift curve slope shelf

2.1.4 Steady Manoeuvring Force and Pitch Sensitivity Criterion

This criterion is essentially similar to CAP in concept, but may be applied to any response type. It is derived by measuring the initial pitch acceleration and steady state normal acceleration for a given longitudinal stick force input, and then evaluating the following formula.

$$|\frac{F_e}{n_p}|_{ss} \times |\frac{\ddot{\theta}}{F_e}|_{max} \tag{2.3}$$

This produces a number which is directly comparable with the CAP value for a given configuration. From work carried out at NLR [20], a proposed reduction in the upper limits for the CAP for a Class III aircraft in the Approach and landing phase was proposed. The level 1-2 boundary was proposed as being at a value of 0.7 rad s^{-2}/g, and the level 2-3 boundary was proposed as being at 2.6 rad s^{-2}/g. A subsequent study [10] proposed a maximum value of 0.45 rad s^{-2}/g, although this was with a much larger aircraft than the Focker F28-6000 which was used in this study. Rossitto et al [21] and Field [2] found evidence to support an increase in the lower level 1 CAP boundary to 0.5 rad s^{-2}/g for the approach and landing phase. Field was dealing with an aircraft with a mass similar to that of the F28, and therefore it seems reasonable that the 0.45 rad s^{-2}/g value is a little low (as the aircraft used in the study is much larger). Hence, a CAP lower boundary of 0.5 rad s^{-2}/g, and an upper boundary of 0.7 rad s^{-2}/g should be appropriate as level 1 boundaries for class III aircraft in the approach and landing phase.

2.1.5 Gibson's Dropback Criterion

Dropback is a phenomenon in the pitch attitude transfer function, and can be seen on figure 2.5. This criterion was developed by Gibson to improve the predictability of the aircraft longitudinal response following the removal of the control input. Specifically, in a pitch rate command attitude hold (RCAH) system, where the steady state pitch rate is constant for a step controller input, dropback is where the pitch attitude drops back to a slightly lower value after the input is removed, and overshoot is where the pitch attitude increases compared to its value when the input was removed.

The actual dropback value for a specified response is strictly an absolute angle. However, the amount of dropback for a given configuration (shown as DB on figure 2.5) depends on the magnitude of the pitch rate response. Therefore Gibson defined limits on non-dimensionalised dropback (shown as DB/q on figure 2.5), which is constant for a specific flight condition for an aircraft, and independent of the magnitude of the aircraft response. This is the value which is referred to as dropback.

Dropback is strictly only relevant to pure pitch rate demand systems, since it assumes that there is a constant pitch rate, but it can be approximated for configurations which have short term pitch-rate like properties, which encompasses most of the rate command laws, plus a classical aircraft response. Configurations with different dropback levels can be seen on figure 2.6. Configuration A is a positive dropback configuration, while configuration B has no dropback, and configuration C has negative dropback, or overshoot.

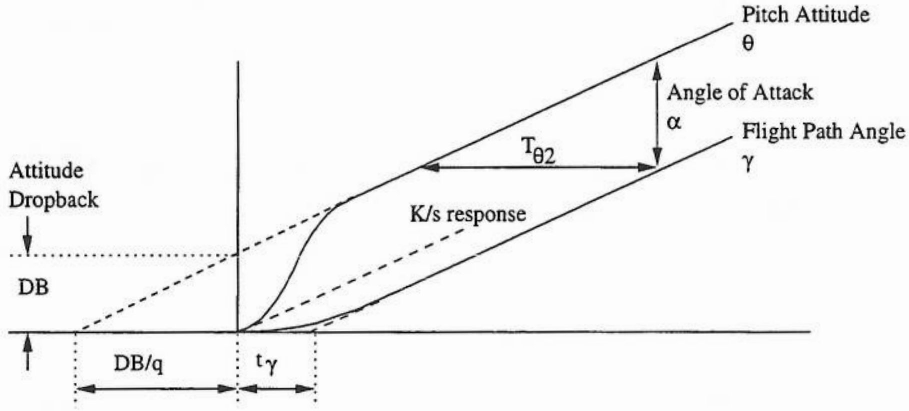

Figure 2.5: Pitch attitude dropback

Negative attitude dropback or overshoot is associated with a sluggish unpredictable response in both flight path control and tracking. Attitude dropback in the range 0-0.25 s is excellent for fine tracking with comments like "the nose follows the stick". Attitude dropback values of greater than 0.25 seconds leads to abrupt response and bobbling (oscillations) for precision tracking tasks. All of these values are related to class IV aircraft undergoing tracking tasks. Attitude dropback has little effect on gross manoeuvring without a target, flight refuelling or landing, provided it is not negative. The limits can be seen on figure 2.7. The Gibson limits shown are those for an in-flight tracking task. Gibson states that a dropback value of up to 1 may be acceptable for the approach and landing phase.

According to Gibson [16], the length of the shelf between $1/T_{\theta_2}$ and ω_{SP} is $T_{\theta_2}\omega_{SP}$. It can be seen that this must be equal to $2\zeta_{SP}$ for there to be zero dropback. A shelf width greater than this results in dropback. An increasing ω_{SP} increases the bandwidth, and for constant $T_{\theta_2}\omega_{SP}$, the nature of the dropback becomes more abrupt and unsatisfactory. This compares to CAP, which is calculated from $\omega_{SP}^2/n_{Z_\alpha}$.

According to French [4], the dropback criterion could be useful if upper dropback limit of 0.3s is

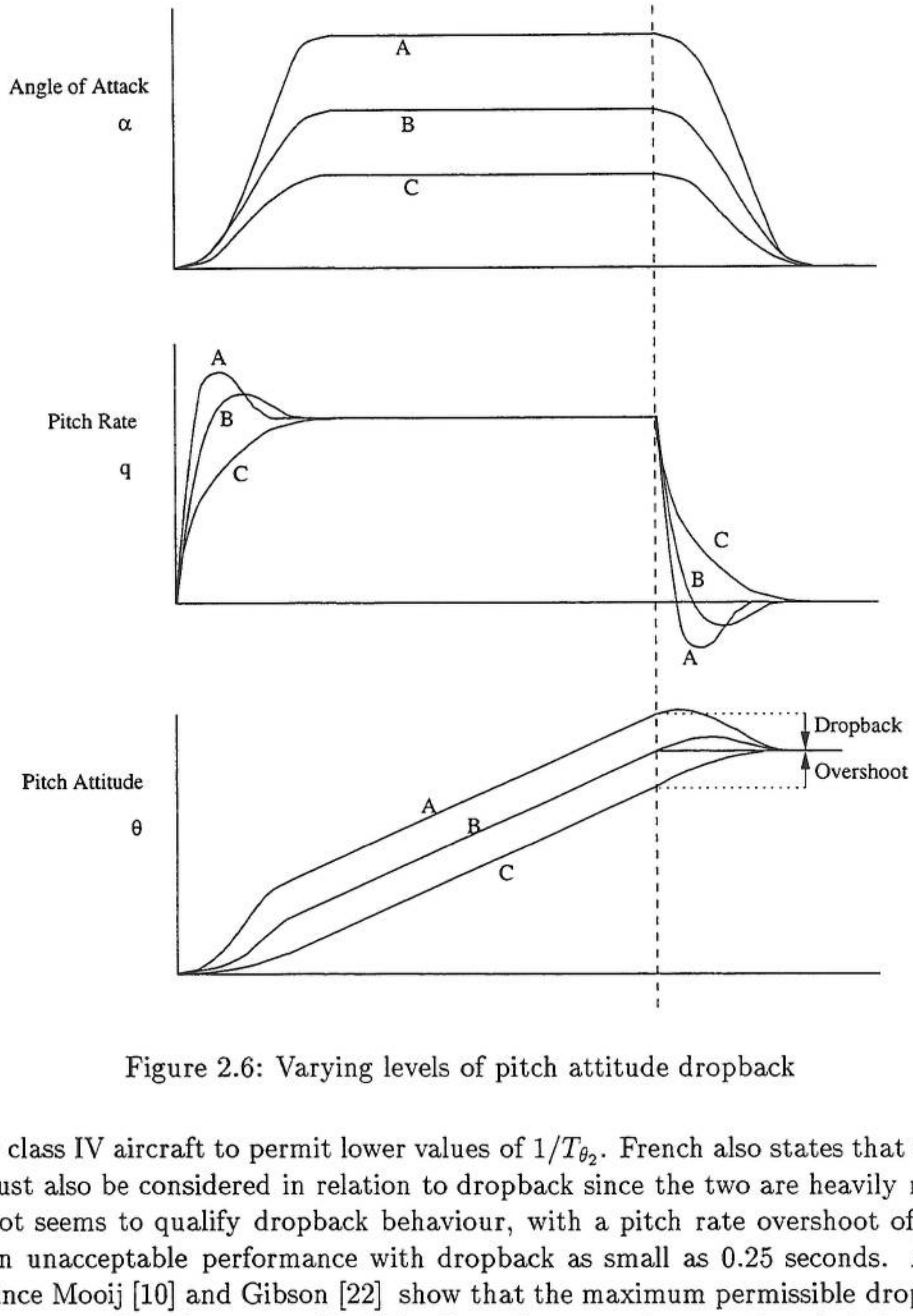

Figure 2.6: Varying levels of pitch attitude dropback

increased for class IV aircraft to permit lower values of $1/T_{\theta_2}$. French also states that the pitch rate overshoot must also be considered in relation to dropback since the two are heavily related. Pitch rate overshoot seems to qualify dropback behaviour, with a pitch rate overshoot of greater than 3 resulting in unacceptable performance with dropback as small as 0.25 seconds. Again, this is reasonable since Mooij [10] and Gibson [22] show that the maximum permissible dropback reduces as the pitch rate overshoot increases. Mooij implies a lower maximum value of pitch rate overshoot of 1.5, compared to Gibson's value of 3 at low dropback values.

Associated with dropback is the flight path delay. A small flight path time delay is excellent for flight refuelling control, but not essential for good gross manoeuvring and does not ensure predictable behaviour, and overshoots in normal acceleration do not cause unpredictable behaviour unless associated with low frequency motions.

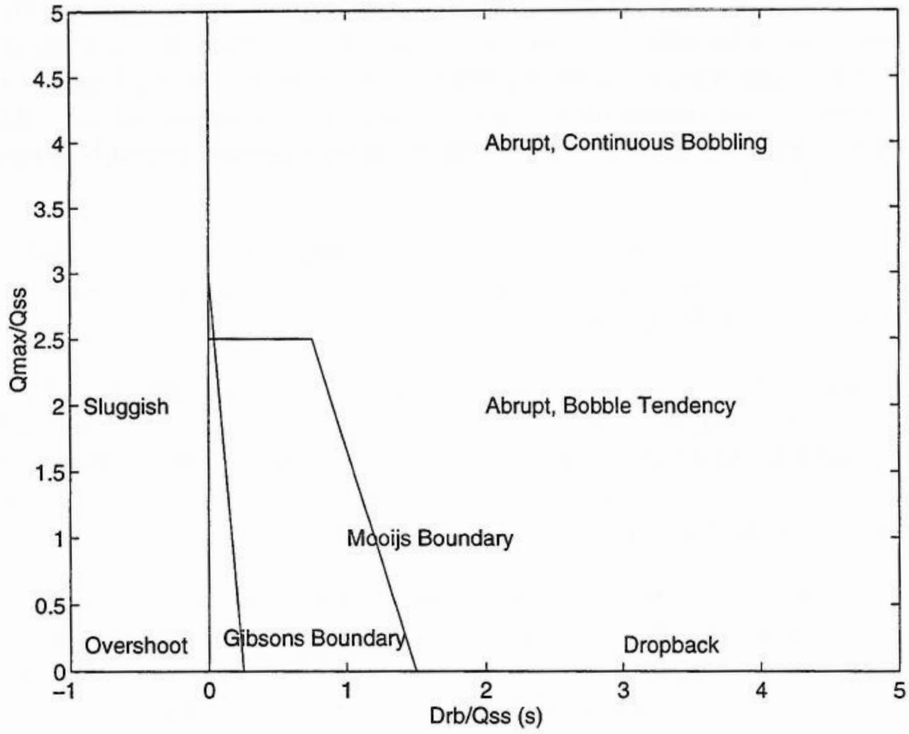

Figure 2.7: Dropback Limits

Flight path delay may be calculated from the following formulae (see figure 2.5).

$$T_{\theta_2} = \frac{DB}{q} + t_\gamma \tag{2.4}$$

Where t_γ is the flight path delay. Therefore, for positive dropback and a constant value of T_{θ_2}, the flight path delay is reduced compared to the zero dropback case. In the limiting case, when T_{θ_2} is equal to $\frac{DB}{q}$ and t_γ is zero, the flight path will return to the value which it had at the point when the stick was released, giving an effective K/s response characteristic in flight path, with no flight path "dropback". However, this may give excessive pitch attitude dropback, which may be deleterious to the pilot opinion rating.

Gibson made two important conclusions from his observations.

1. Pitch attitude dropback must be zero or positive, and
2. Some pitch rate overshoot is always necessary for optimum handling, i.e. pitch rate overshoot is required to minimise dropback for inputs with tracking tasks, and to rapidly generate the angle of attack increment required for crisp flight path response in gross manoeuvring and landing etc.

Command path filtering may be used to augment the dropback, using pole-zero cancellation. For precision tracking, zero dropback is preferred when combined with a high short term mode natural frequency since it gives the near-optimal K/s flight path response for closed-loop flight path control. However, if this is not achievable, dropback less than 0.25s is better than overshoot. High damping provides the widest achievement (with variation in altitude and wing loading) of the optimum short period frequency for zero dropback. Accordingly, for low order aircraft with a simple pitch damper augmentation, a low margin with its high inherent damping should be aimed for if precision handling is required.

Gibson [16] states aircraft have very high manoeuvre margins at approach speeds, and as a result their short period frequencies may not be as low as might be expected for their pitch inertia. This may increase the dropback for a given $1/T_{\theta_2}$ values.

For aircraft with positive dropback, including a dropback filter (as a lead/lag filter in the command path) will increase the $1/T_{\theta_2}$ frequency, and therefore decrease the size of the shelf between $1/T_{\theta_2}$ and ω_{SP} in the attitude bode plot. This results in the aircraft retaining integrator-like properties (K/s) over a greater range of frequencies due to the greater value of $1/T_{\theta_2}$, with the benefits associated in precision tracking [4].

In theory, the dropback criterion only applies to conventional and rate command systems where the effective stick-free static stability is zero, i.e. the stick must be returned to zero to stop the pitch rate. However, it may also be applied to other rate demand systems, as long as they exhibit rate-like characteristics in the short to medium term. The authors experience has shown that dropback is valid with these systems as long as the there is a reasonably constant slope in the pitch attitude response between approximately 5 and 10 seconds.

In summary [4], the dropback criterion is effective for assessing the acceptability of an aircraft's open loop pitch attitude response for precision tracking tasks. For positive dropback configurations, modifying T_{θ_2} to obtain zero dropback will not only provide a good (predictable) open loop response where the attitude remains fixed at an existing value when the input is removed, but also provides a better closed loop response at low frequencies. For approach and landing, dropback is an important consideration, not only for pitch attitude control, but also for the effect on the flight path delay.

NLR Modified Gibson Dropback Criterion

The NLR Modified Gibson criterion defines overshoot and dropback limits for class III aircraft. This modification was made by Mooij at NLR [10]. The complete equations of motion must be used [11], and this criterion has tighter constraints than Gibson's original criterion [22]. The upper horizontal cut-off is established from space shuttle criterion and Mooij's experiments [11]. The criterion permits much greater dropback than Gibson (fighter combat manoeuvring) but allows less q_{max}/q_{ss}. The boundaries for Mooij's modified criterion can be seen in figure 2.7.

2.1.6 Gibson's Phase Rate Criterion

According to French [4], the phase rate criterion uses the phase crossover frequency and a custom defined phase rate parameter to characterise the open loop pitch attitude frequency response [23]. Phase rate is a measure of the slope of phase curve for frequencies approaching and just past the phase crossover frequency, i.e. the critical region. Accordingly, the phase rate criterion correlation parameters are considered more suitable than those utilised by the bandwidth criterion.

This criterion was defined to help prevent the PIO problem in aircraft with high order systems. Gibson found a good correlation between PIO data and the rate at which the pitch attitude phase lag increases with frequency in the crossover region (i.e. phase rate), which is the frequency at which the PIO's tend to occur. A low order response tends to attenuate quickly to a high frequency crossover with a low phase rate while a high order response tends to attenuate slowly towards a low frequency crossover with a high phase rate. Gibson also found an equal applicability to the landing or target tracking tasks.

Accordingly, as a result of the low phase rate and subsequent high crossover frequency and attenuation, a low order response is less likely than a high order response to exhibit PIO tendencies since

1. The gain margin is greater (greater margin for the pilot to increase his gain without the system going unstable), and
2. The stick pumping amplitude is smaller.

In applying the phase rate criterion, the values of the phase rate and phase crossover frequency are computed, and compared to the known limits. A phase rate of less than 100 deg/Hz is required to ensure PIO is avoided. Limits can also be placed on the phase rate if the requirement is not

Although the phase rate criterion is an open loop criterion, its purpose is to confirm that acceptable closed-loop operations can be achieved without any likelihood of PIOs. To do this, the criterion examines the characteristics of the open loop pitch attitude frequency response and compares them against that of a low order aircraft, which rarely exhibit PIO tendencies. The limits imposed by the criterion merely try to ensure that suitable margins exist for the pilot to introduce his own gain and phase compensation without threatening stability. Accordingly, the approach followed is very similar to the bandwidth criterion. PIOs resulting from stick pumping manifest as a result of insufficient bandwidth and stability margins. If the phase crossover frequency is within the region of piloted crossover and the phase rate is high, increasing pilot gain or introducing additional phase lag will result in a rapid convergence of ω_{0dB} and ω_{-180}, and hence closed loop instability. In the landing phase, which has been shown to be a high gain demanding task, the combination of low phase crossover frequency (i.e. too low bandwidth) and high phase rate will result in PIO tendencies.

In relation to stability considerations, the slope of the phase curve is most critical for frequencies approaching and just after the phase crossover frequency, since this will determine the frequency at which the phase and gain margin decrease with increasing gain or phase lag. The PIO region defined by Gibson will determine the PIO frequency (which will be greater than ω_{-180}), since it is here that the response first becomes unstable. Accordingly the use of phase crossover frequency and phase rate as correlation parameters give the criterion good credibility as these parameters relate directly to the pilot-vehicle closed loop stability for a given task.

In Blagg's analysis of handling qualities criteria [5], he describes phase rate as providing excellent design guidance and should be used, subject to validation.

2.1.7 Hoh's Proposed criteria for precision flare

With respect to the discussion given within this paper [12], it is necessary that the response type be conventional or attitude command. The phugoid or long term mode may or may not be representative, but that is of no consequence for the flare manoeuvre, and therefore not a consideration in the response type definition for this task. Hoh states that care must be taken to ensure a K/s type response(see section 2.1.2) in the flight path response in the piloted crossover region. Data indicates a flight path bandwidth of greater than 0.8 rad s^{-1} ensures reasonable region of adequate K/s in the flight path response.

Good direct control of the flight path vector assumes that attitude control is not a problem, and can be essentially ignored by the pilot. This is assured by requiring an attitude bandwidth of at least 2.5 rad s^{-1}. The criterion is summarised below,

Attitude Dynamics

The following requirements are specified.

$\omega_{BW_\theta} > 2.5$ rad s^{-1}

Phase Delay $t_p < 0.1$s

Flight Path Response

The short term angle of attack response is assumed to be a step with zero slope achieved before 5 seconds. If the short term response is not a step or questionable then $\omega_{BW_\gamma} > 0.8$ rad s^{-1}.

Required energy to flare -

$\frac{d\gamma_{max}}{d\theta_{SS}}$ >0.7 for level 1 qualities

$\frac{d\gamma_{max}}{d\theta_{SS}}$ >0.5 for level 2 qualities

This last requirement is included to ensure that there is sufficient energy to change the flight path vector. The minimum values for this were generated from NASA Ames data.

2.1.8 Control Anticipation Parameter Extension

For a classical aircraft, the CAP criterion is calculated as a function of the short period mode natural frequency and damping, $1/T_{\theta_2}$, and the airspeed. For non-conventional response types, the aircraft does not have a conventional short period mode; rather a short term mode, which for a pitch rate response type is the principal manoeuvring mode.

CAP was initially intended as a criterion for precise flight path control, and it was also initially targeted at stick pumping [24]. Therefore it is especially relevant to the approach and landing task since this is probably where the most precise flight path control is required for a civil transport aircraft.

MIL-STD-1797A [18] states that the pilot sometimes resorts to stick pumping to achieve better precision. This technique is likely to be used if the short period frequency is too low, or the phugoid is unstable, although it has been observed in other circumstances. Some important manoeuvres, such as correcting for a offset on final approach call for simultaneous, coordinated use of several controls.

Analysis of the theory behind the original CAP criterion shows that it should be valid for alternate response types which have a constant load factor for a step input, such as rate demand systems. This is because the denominator dynamics cancel in the derivation of CAP to leave the numerator dynamics (which are unchanged for alternative response types with the exception of the zero introduced by the controller).

The CAP parameter is approximated by the initial pitch acceleration divided by the peak acceleration during the first 10 seconds. Therefore CAP was modified for the alternative response types as follows.

The initial pitch acceleration may still be calculated from the aircraft response characteristics. However, for most control laws, and for non-constant speed approximations, there will be a non-constant steady state normal acceleration value. However, for most response types, there will still be a first peak normal acceleration value. The Generic CAP (GCAP) extension proposes to calculate the effective steady state normal acceleration from the value of this peak, and the short term mode damping ratio.

This may be calculated from control theory. According to Raven [25], the relationship between the height of the first peak and the steady state value can be calculated as follows for a second order system.

$$\frac{y_{max}}{y_{ss}} = 1 + \exp\left(\frac{-\zeta\pi}{\sqrt{1-\zeta^2}}\right) \tag{2.5}$$

Therefore as long as the damping ratio is known, the relationship can be determined. Therefore the definition of CAP, assuming a first order approximation may be defined as follows.

$$CAP = \frac{\ddot{\theta(0)}}{N_{Z_{ss}}} \tag{2.6}$$

$$CAP = \frac{\ddot{\theta(0)}}{N_{Z_{pk}}} . \frac{N_{Z_{pk}}}{N_{Z_{ss}}} \tag{2.7}$$

Therefore

$$GCAP = \frac{\theta(\ddot{0})}{N_{Z_{pk}}}.\left(1+\exp\left(\frac{-\zeta\pi}{\sqrt{1-\zeta^2}}\right)\right) \tag{2.8}$$

This suggests that if the damping ratio of the short period mode (or short term mode for a non-conventional response type) is known, along with the peak value of normal acceleration and the initial pitch acceleration, the CAP value may be calculated.

The following assumptions are made

1. The CAP hypotheses are valid.
2. The initial normal acceleration peak is related to the steady state value, assuming a second order system. This implies that the response is dominated by a second order response.
3. The pilot is sensitive to the peak value of normal acceleration, as opposed to the steady state value. This is reasonable as the pilot is unlikely to ever let any long term mode develop.
4. The initial pitch acceleration is independent of the short term mode damping. This is reasonable as the initial pitch acceleration ($\ddot{\theta}$ is considered over the first 0.1s).
5. The damping ratio of the short term or short period mode is less than unity so that there is at least one peak in the normal acceleration response.

Comparison between the experimentally derived GCAP and the calculated value for CAP show that the difference between the two values is less than 10 % for 80 % of the time, and less than 5 % for 60 % of the time. This seems like quite a close correlation, especially considering the approximations which have been made in the initial CAP analysis. Bihrle [24] states that the calculation for CAP using the following formula is only 10 % accurate due to the assumptions made in order to simplify the equations. This is not to say that the current CAP boundaries are in question, since they were determined from the approximation. All it specifies is that the GCAP analysis presented here may have up to approximately a 10 % difference between the value which it gives, and the actual CAP value. In addition, CAP is calculated assuming that long term dynamics are not present. This will have an effect on the measured values of GCAP since long term dynamics are assumed to be present.

$$CAP \approx \frac{\omega_n^2}{n_\alpha} \tag{2.9}$$

Therefore to expect the equations presented previously to be exact is unjustified, and the equations quoted before should give a sufficiently accurate answer.

This implies that CAP may now be used with alternative response types, since characteristics which are present in both the classical and non-classical aircraft responses, namely the initial pitch acceleration, the short term mode damping ratio and the first peak normal acceleration are being used for the computation of the CAP parameter. The fact that the long term response of the non-conventional law is different from the long term response of a classical aircraft should not pose a problem since CAP was initially derived as criterion for precise closed loop flight path control [24], and therefore the pilot will never let the configurations respond to an input for more than a few seconds without modifying his input. The boundaries used to develop the criterion should therefore still be valid.

It is seen that the peak normal acceleration value can be predicted from the steady-state response. It is not known whether the pilot is sensitive to the steady-state value, or the peak, which are both directly related by the damping ratio. Therefore, for the CAP analysis considered here, it is proposed that the pilot is sensitive to the peak value, and that the steady-state value was used in the calculations since it is mathematically easier to derive, being found directly from the reduced order aircraft approximation, and the boundaries have been defined using this value. Analysis shows that for a conventional aircraft, the CAP value increases with increasing dropback. This relationship can be easily derived. Both of the relationships $\ddot{\theta}/Nz_{pk}$ and $\ddot{\theta}/Nz_{ss}$ increase as the value of the dropback increases. However, since pitch rate command laws have no steady-state value of normal acceleration in the short term, the latter is meaningless for a pitch rate command law. Therefore it is suggested that the former is used.

2.2 Artificial Static Stability for non-conventional response types

Much work has been performed investigating the effects of aircraft speed stability. A study performed at NLR in the Netherlands using a piston engine-powered Beech Queen Air [26] concluded that positive stick force stability results in reduced RMS airspeed deviations and reduced maximum deviations from the reference airspeed, and also resulted in reduced (subjective) pilot effort in airspeed holding. This study was then extended using a Focker F28 MK6000 [27] which considered varying levels of static stability. This study found that a speed force gradient of 5 knots/lb was more desirable than zero or the higher forces required for 2 knots/lb, but these results may have been clouded by the fact that the higher levels of stability had a negative long term mode damping ratio (they were mechanised using pitch rate dynamics as the short term mode response characteristic). At low levels of speed stability, there was a modest reduction in airspeed error, at the expense of low increases in glideslope deviations and pilot stick force deviations. These values can be compared to the FAR-25 quoted minimum level of 6 knots/lb.

It has been demonstrated that artificial static stability can be introduced by summing an effective stick force, calculated from the airspeed or angle of attack error term, with the pilot's pitch inceptor demand. This gives positive speed stability, since the pilot is required to hold a constant stick force to maintain the speed error, and depending on the dynamics of the response type, the aircraft will try to return to the trimmed speed when the stick is released. This phenomena is considered in detail in this section.

The speed error term is calculated by taking the difference between the current airspeed and the reference or trimmed airspeed. For the purposes of the controller in this set of evaluations, the trimmed airspeed was calculated from the position of the trimmer which is usually used to move the horizontal stabiliser. The sense of movement of the trimmer was that of a conventional aircraft, such that winding the trimmer rearwards or pulling down on the thumb-mounted trim switch lowers the reference speed, and vice versa.

The major difference between using angle of attack and airspeed feedbacks is in the numerators of the appropriate transfer functions. They are as follows :

$$N^{U}_{\delta e} = K^{U}_{\delta e}(-2.981)(1.492)(2.921) \quad (2.10)$$

$$N^{\alpha}_{\delta e} = K^{\alpha}_{\delta e}(16.249)[0.095, 0.2232] \quad (2.11)$$

$$DEN = [0.051, 0.151][0.608, 0.747] \quad (2.12)$$

where K (a) [ζ,ω] is the appropriate Numerator / Denominator, in which K is the DC gain, (a) corresponds to a single pole (s+a), and [ζ,ω] corresponds to the complex pair $[s^2 + 2\zeta\omega s + \omega^2]$.

These transfer functions describe the behaviour of the Generic Regional Aircraft at an airspeed of 120 knots, with the gear down, and with the flaps in a landing position. It can be seen that the airspeed to elevator transfer function has a right hand plane zero, and this will cause problems if the airspeed to elevator feedback is increased. The severity of the problem depends on the location of the augmented aircraft poles before the airspeed feedback is used. If they are all sufficiently in the left half plane, then a large value of airspeed feedback is possible before one or more of the poles becomes unstable. However, if these poles are not sufficiently in the left hand plane, little augmentation will be possible before the system becomes unstable. This can be seen on figure 2.8.

2.2.1 Use of Speed Feedback

The effects of introducing speed stability on the different control laws under consideration using speed feedback can be found in the following section.

Pitch Rate

The effect of feeding back speed error in a pitch rate demand system produced two real roots. These migrated into a complex pair as the speed error gain increased, and produced a long term mode with characteristics similar to the phugoid mode. As the gain was increased, the damping rapidly reduced from above unity (due to the two real roots) down to 0.04, which is the minimum phugoid damping required to meet level 1 requirements.

Increasing the stick force to speed error gain increased the frequency of the long term mode produced. This corresponds with Chalk's findings [28], where increasing the phugoid natural frequency (ω_{ph}) resulted in increased stick force feel for airspeed deviations. Also, as previously stated, no significant improvements were made to handling for a phugoid damping ratio (ζ_{ph}) greater than 0.15 [28].

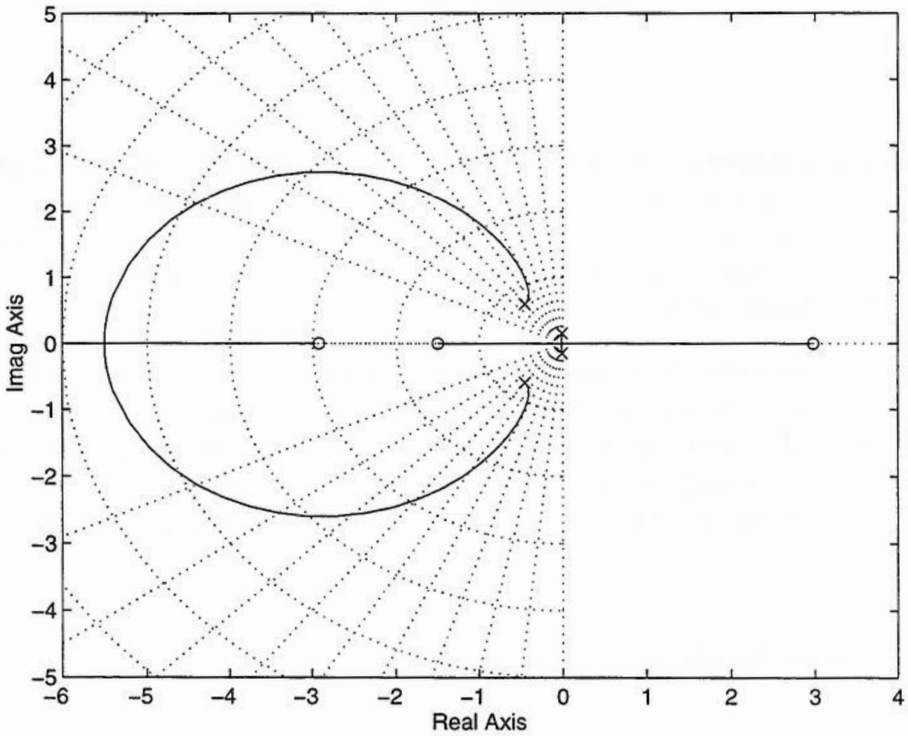

Figure 2.8: Airspeed to Elevator Root Locus Plot

Therefore the recommended damping ratio adopted is 0.15 for the phugoid mode, and in order to retain semi-conventional characteristics, this damping ratio should not be exceeded. For the pitch rate control law considered here, it implies that the speed error to stick force gain must be at least 0.5 lb/ ms^{-1}, or 0.25 lb/kt. This therefore gives a speed change of about 4 knots for a stick input of 1 lb. Therefore, in order to ensure that the 6 kt/lb minimum is exceeded, a higher gain is selected at 0.6 lb/ ms^{-1}. This gives a long term mode damping ratio of 0.11 (for the approach) and a natural frequency of 0.24 rad s^{-1}, which corresponds to a time period of 25 seconds.

Normal Acceleration

The use of speed feedback with normal acceleration control laws is not as straightforward as with the pitch rate based laws. When the speed feedback gain is increased, the damping and natural frequency of the long term mode vary as with the pitch rate law, i.e. the damping decreases and the natural frequency increases with increasing feedback gain. However, the damping of the short term mode can increase significantly with increasing speed error gain. Therefore the speed error feedback must be taken into account when designing the main control laws.

The speed error feedback gain must be significantly reduced as the speed increases for the long term mode to remain stable, assuming no other actions are carried out to stabilise the long term mode. This is due to the non-minimum phase effect exhibited with the aircraft used. Essentially, there is a right half plane zero, to which the long term mode poles will migrate if the speed feedback error is increased significantly.

C*

Similar analysis was carried out for a C* control law. Not surprisingly, the effects of speed feedback on the C* control law at low speed are identical to those of the pitch rate law since C* is essentially identical to a pitch rate law at low speeds. At high speed, the effect is similar to normal acceleration where the long term mode damping is reduced or even becomes negative if the long term mode damping is not increased artificially.

This does not give the same stick force requirements per unit speed change, but it has been shown that the pilot is sensitive to normal acceleration with respect to stick force at high speed, and angle of attack (or essentially speed) at low speed. In addition, a civil aircraft is likely to be flown using the autothrottles for the majority of the time when it is in up-and-away flight, and therefore the requirement can probably be relaxed. The 0.2 lb/m/s gives about a 10 knots per lb stick force at 240 knots.

2.2.2 The use of Angle of Attack Feedback

The effect of angle of attack feedback was investigated. The aim was to produce a control law which was angle of attack stable in the long term. This was mechanised by determining a reference angle of attack value from the trim wheel, and then subtracting this value from the actual angle of attack to determine an angle of attack error. This was then converted into a stick force demand in the same way as with the airspeed feedback, and summed with the pilot's stick force demand. The reason why it was mechanised in this way was due to the fact that the integrator in the control law works to minimise the loop error, which for the basic control law is pitch rate, C* or normal acceleration.

The use of angle of attack feedback had a much greater effect on the short term mode than speed feedback. Again, using angle of attack feedback generates a complex long term mode of a similar natural frequency to the phugoid, although the damping tends to be higher, especially at low values of angle of attack error to pitch rate demand gain. This is due to the location of the poles on the real axis. However, problems were experienced in achieving desired dropback values, although the dropback could be slightly modified by using a prefilter in the command path.

The angle of attack to elevator root locus can be seen on figure 2.9. Due to the fact that there are no right half plane zeros, the angle of attack feedback can be increased to whatever value is required without any poles becoming unstable.

2.2.3 Comparison between Angle of Attack and Airspeed Stability

Upon investigation, it was found that any amount of angle of attack feedback could be used. This is due to the location of the zeros in the angle of attack transfer function. Since they all lie in

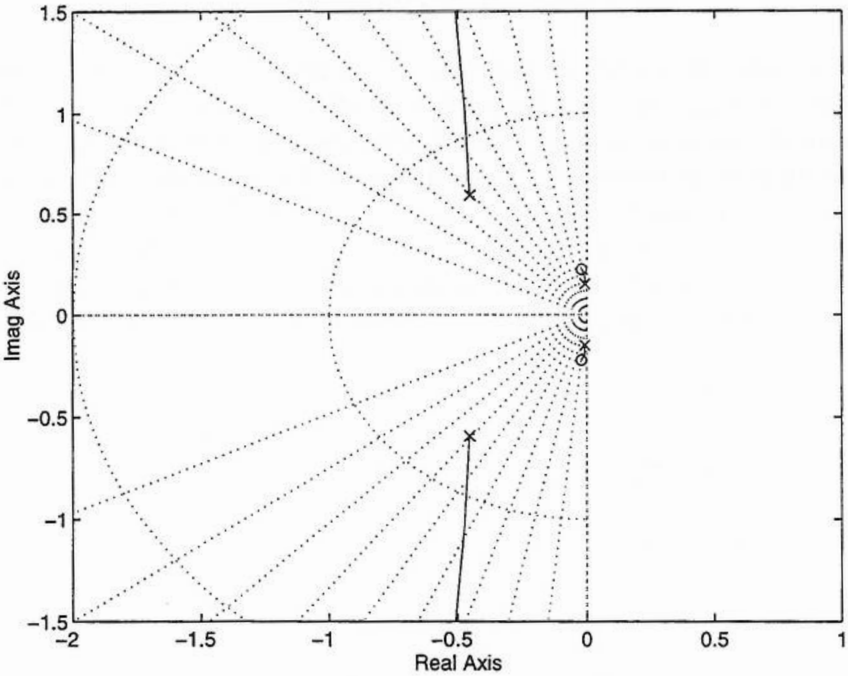

Figure 2.9: Angle of Attack to Elevator Root Locus Plot

the left half plane, and the two closest to the origin approximate the phugoid poles, increasing the angle of attack feedback gain to stick demand will generally cause the two slowest poles to migrate towards them.

Therefore angle of attack feedback may be used to stabilise any configuration and to provide a long term angle of attack demand system.

2.3 Control law concept discussions

This section provides some preliminary discussion concerning the different control law concepts under consideration. Practical implementation issues such as structural filters, gust filters and anti-alias filters have not been considered.

2.3.1 Controller Theory

Proportional plus integral control is used extensively in the control laws designed. This method was selected as opposed to pole / zero cancellation as it is the method which is most likely to be used in practice, and it can be tailored to the specific needs of the problem.

Many methodologies for dealing with P+I controller design exist. For aircraft, many consider the constant speed approximation for the aircraft, where a P+I controller will introduce an additional pole and zero in the basic aircraft transfer functions. Methods then exist for using feedforward gains to enable the pole and zero to be cancelled.

In addition, the value of the feedforward gain has a great effect on the dropback characteristics of the control law through the controller providing effective phase lead or lag through its pole and zero. It is generally referred to as a control quickening gain, and as such, it can be used to increase or reduce the amount of dropback. Since dropback has been shown to be important in aircraft handling qualities, it is suggested that the pole / zero cancellation using a constant speed model is not suitable since it does not explicitly consider either of these effects, although dropback may be compensated for by using a filter. Configurations which are designed without both of these effects in mind may receive lower ratings due to the undesirable dropback or gain characteristics.

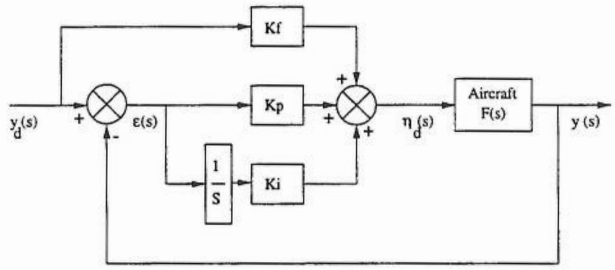

Figure 2.10: Proportional + Integral Controller with Feedforward

A basic controller conceptual diagram can be seen in figure 2.10. The overall transfer function may be developed as follows.

$$\eta_d(s) = y_d(s)Kf + \epsilon(s)\left(Kp + \frac{Ki}{s}\right) \tag{2.13}$$

$$y(s) = F(s)\eta_d(s) \tag{2.14}$$

where

$$F(s) = \frac{N(s)}{\Delta(s)} \tag{2.15}$$

$$\epsilon(s) = y_d(s) - y(s) \tag{2.16}$$

Therefore,

$$y(s) = y_d(s)KfF(s) + (y_d(s) - y(s))\left(Kp + \frac{Ki}{s}\right)F(s) \tag{2.17}$$

Collecting terms,

$$y(s)\left(1 + F(s)\left(Kp + \frac{Ki}{s}\right)\right) = y_d(s)F(s)\left(Kf + Kp + \frac{Ki}{s}\right) \tag{2.18}$$

Therefore substituting equation 2.15 and rearranging,

$$\frac{y(s)}{y_d(s)} = \frac{\frac{N(s)}{\Delta(s)}\left(Kf + Kp + \frac{Ki}{s}\right)}{1 + \frac{N(s)}{\Delta(s)}\left(Kp + \frac{Ki}{s}\right)} \tag{2.19}$$

which can finally be arranged as

$$\frac{y(s)}{y_d(s)} = \frac{N(s)\left(s(Kf + Kp) + Ki\right)}{s\Delta(s) + N(s)(sKp + Ki)} \tag{2.20}$$

Therefore, it can be seen from equation 2.20 that the position of the zero introduced by the controller is influenced by the feedforward gain while the position of the pole introduced by the controller is not. Therefore the appropriate combination of the Ki, Kp and Kf gains may be used to provide and effective phase compensation if required, or the zero may be positioned to cancel the pole introduced by the controller.

2.3.2 Conventional Aircraft Discussion / Angle of Attack response type

Field [2] found that the angle of attack configurations were rated better than all of the other configurations tested for the approach and landing task for a transport aircraft. The pilot's preferred the conventional response of these configurations with minimal trim requirements for flight path changes, positive force for speed changes and monotonic forces in the flare. These configurations also have a conventional flight path to pitch attitude consonance since the long term angle of attack behaviour is constant for a given step input.

Therefore, the pitch attitude to flight path consonance exhibited by a conventional aircraft is of paramount importance for the approach and landing task since the pilot is essentially trying to control the aircraft flight path through reference to the aircraft pitch attitude.

Increasing the angle of attack feedback gain resulted in a trend towards better ratings. With increasing angle of attack feedback, the short term mode frequency was increased. However, larger forces were required to hold the aircraft off-trim, and to keep the aircraft level in turns where larger angle of attack changes were required. The response to turbulence was also greater. Pilot's comments indicated that the initial response was better with these configurations, but did not seem to hold attitude, and predictability of the final attitude was not as good as required. Attitude, airspeed and flight path control also required higher workload in turbulence.

Angle of attack configurations tended to hold angle of attack, and in turbulence and ground effect there tends to be a considerable low frequency variation in attitude and airspeed which required increased pilot attention and workload to control. The aircraft were repeatably described as ponderous in the IFR approach and difficult to control in the flare and touchdown. The phugoid mode, which becomes less damped, and moves towards higher frequencies as alpha feedback is increased. becomes more noticeable, and likely to be the cause of these observations for the extra-high angle of attack augmentation configurations.

2.3.3 Pitch rate discussion

Much has been written about pitch rate control laws, and the key elements have been reproduced here. It must also be remembered that classical aircraft are often referred to as pitch rate demand in the short term, and angle of attack demand in the long term.

One characteristic of pitch rate control laws is their resistance to pitch gusts compared to classical unaugmented aircraft, and this favourable characteristic is borne out in many handling qualities evaluations [29]. Therefore, the pitch rate command attitude hold response type is significantly different to the conventional response type, and it is not applicable to apply CAP simply by substituting the pitch rate short term mode natural frequency in the place of the short period mode natural frequency due to the differences in aircraft response, even though this substitution is commonly made.

In order to give conventional flare characteristics, a modification is often made to the flare law. This is done to give angle-like properties, and to therefore give monotonic forces in the flare. Therefore the law can be modified by adding a 'front end' onto the control law which gives angle-like properties. At some reference height, the pitch attitude is memorised by the control law, and in order to hold a pitch attitude greater than the selected value, a constant stick force needs to be held. Therefore to increase the pitch attitude in the flare to maintain the flight path angle as the angle of attack increases, a monotonic ramp input is required, which gives a conventional-like characteristic. The gain between the 'pitch attitude error' and the stick force can be selected to give a suitable characteristic, as can the height at which the flare law is selected. This can be seen in figure 2.11. By modifying the gains Ka (for speed stability), Kb (for the flare law) and Kc (for angle of attack stability), the control law characteristics may be modified.

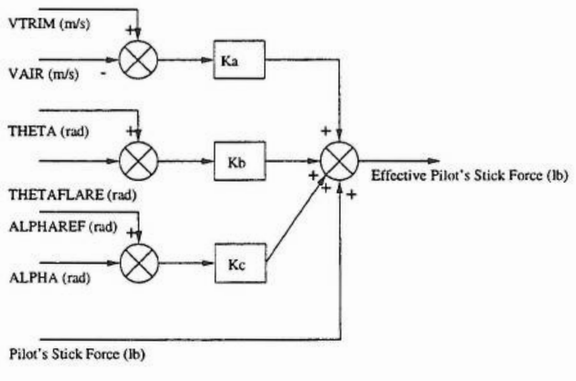

Figure 2.11: Control Law 'Front End'

One investigation into large aircraft flying qualities in the approach and flare found that pitch rate command attitude hold configurations had better characteristics than the alpha command [14], primarily due to the attitude hold capability. This made precise touchdown control easy due to the gust rejection characteristics. These configurations were also found to be very predictable, which was especially useful with the short aft-tailed configuration since it did not give as much of a Nz cue due to the centre of rotation effects, in the same way as the space shuttle. An identical technique was adopted here as that used to land the shuttle. The pilots were also impressed with the level turn feature, which removed much of the workload present for the alpha command configurations in maintaining altitude during a turn manoeuvre. When these configurations were trimmed, and the pilot had the correct thrust setting, they tend to hold airspeed very well, even in turbulence.

2.3.4 C* Discussion

C* was initially developed as a handling qualities parameter by the Cornell Aeronautical Laboratories, and is the sum of the aircraft pitch rate and normal acceleration, where K_q is a constant.

$$C^* = N_Z + K_q q \tag{2.21}$$

At low speed, the majority of the contribution to the C* parameter will be from the aircraft's pitch rate, and at high speed, the majority of the contribution will be from the aircraft's normal acceleration. Therefore a C* command law will essentially have pitch rate like characteristics at low speed, and normal acceleration like characteristics at high speed. Therefore the comments concerning pitch rate laws at low speed have been considered when designing C* laws at low speed, see section 2.3.3.

C* can be considered as a a blend of the numerators of the normal acceleration and pitch rate transfer functions. Depending on the precise value of the constant K_q, here shown to be 12.4 m s^{-1}/rad, this blend can be varied. For the law to have largely pitch rate characteristics, the value for K_q generally needs to be approximately 100 m s^{-1}/rad for the Generic Regional Aircraft. For normal acceleration-like characteristics, it needs to be considerably less than 12.4 m s^{-1}/rad.

Since C* is based around a rate demand system, it has the same problems in the flare as the pitch rate demand system, and therefore some form of flare law is required, see section 2.3.3. The normal acceleration law was effectively a C* law, but with normal acceleration like properties. Pitch rate was blended with the normal acceleration in order to achieve the necessary damping for both the short and long term modes, see section 2.3.5.

2.3.5 Normal acceleration discussion

A normal acceleration command law, or manoeuvre demand law is where the pilot demands normal acceleration with the pitch inceptor. These command laws are commonly used in fighter aircraft, where it has been shown that the pilot is sensitive to normal acceleration, and also in the Airbus fly-by-wire aircraft.

Problems exist with normal acceleration laws due to the fact that feeding back normal acceleration or the integral of it does not increase the damping of the short term mode of the aircraft. Therefore it is necessary in practice to add some pure pitch rate feedback to the elevator to achieve this. In addition, if damping of the long term mode is required, then pitch attitude like damping, or integral pitch rate feedback is required.

Field [30] found a slight preference for flight path measured at the pilot's position rather than at the centre of gravity for the flight path demand systems. This is more apparent with an in-flight simulator since it can reproduce the normal acceleration cues whereas a fixed-base simulator cannot [14].

Moorhouse [31] postulated that landing performance can be improved by decoupling the flight path from the airspeed responses. This is achievable using a normal acceleration control law concept with an autothrottle, since the airspeed is controlled directly by the autothrottle action, while the flight path is controlled directly by the pilot's inceptor.

As with the pitch rate demand system, some form of flare law is required as the normal acceleration law also has rate-like characteristics in the flare, see section 2.3.3.

2.4 Cooper Harper Flying Qualities Rating Scale

The Cooper Harper flying qualities rating scale is generally used to rate the flying qualities for a particular aircraft configuration performing a particular task.

It is a flying qualities scale that measures both task performance, and workload. The pilot is asked to assess his actual performance compared to desired or adequate performance levels. Once the performance level has been decided, a further refinement of the flying qualities rating is made by the pilot qualitatively assessing his workload.

The flying qualities ratings produced are for a particular configuration being flown for a particular task, and substantially different ratings may be found for a different task.

A copy of the rating scale may be found in Appendix D.

2.5 Workload

Workload is of fundamental importance to aircraft flying qualities. Workload is thought to be a multi-dimensional construct combining the demand imposed on the pilot as he attempts to achieve the flight objective and the momentary capacity of the pilot to meet these demands [32].

Roscoe and Ellis proposed a definition for workload, which is modified slightly from Cooper and Harper's definition as follows :

> Workload is the integration of mental and physical effort required to satisfy the perceived demands of a specified flight task.

With the advent of single crew aircraft, pilot workload is of vital importance since if the workload is too high or low, it can be detrimental to flight safety. Workload is a difficult quantity to measure, since it is qualitative by nature, and people will have different ideas about similar workload levels.

There is also a lack of specific workload information for handling qualities investigations. Since workload is implied in the Cooper Harper rating scale, little other information concerning workload is presented for the majority of the handling qualities literature considered.

Workload is still a useful measure, especially as it can be used to distinguish between cases where the performance for a given task across a variety of pilots is constant, but the workload levels are significantly different [33].

2.5.1 Methods for measuring workload

There are many different workload measures, and not all of them are equally sensitive to types of workload. They are described briefly as follows.

Timeline Analysis

This is a method which computes a predicted workload value depending on the task. It is not good for tasks in parallel, and is too conservative. For timeline analysis, it is necessary to define specific flight phases within a given task or evaluation. The phases should have start and finishing events.

NASA Task Load Index (TLX)

NASA TLX [33] and [32] is a sophisticated form of workload measurement. It distinguishes between different causes of workload where there is similar performance.

It characterises the demands of a given task in two ways. The first is the demands imposed by the task on the participant, and these are mental, physical and temporal demands. These are different from the demands due to the interaction between the participant and the task, which are effort, performance and frustration.

NASA TLX rates all of the six mentioned types of demand against each other, and then the subject is required to state the importance of each in the task. From this, an overall value of the workload is determined, and also the importance of each of the six demands in contributing to the workload. This has been used for a variety of experiments in flight, including assessment and training evaluations [33]. It has been demonstrated to be a reliable workload scale.

Bedford Scale

The Bedford scale was initially developed by Roscoe [34] and others at RAE Bedford. It is a 10 point rating scale, and has a similar format to the Cooper Harper scale. It is based on the concept of spare capacity, and was developed with the assistance of practising test pilots, and has been used by a large number of pilots in various flight trials and workload studies.

In the same way as Cooper Harper, the Bedford scale is designed for use with a specific piloting task. The Bedford rating is compiled by either completing up to three questions in a decision tree, or by an experienced pilot calling out a number.

The scale has been used in a variety of situations, from assessing aircraft handling qualities for a specific task to assessing the impact of technology, such as glass cockpits on pilot workload and effects due to the aircraft operating in specific conditions such as over the North Sea [34].

The Bedford scale is acceptable for a limited evaluation, but can be restrictive due to its simplicity. It does not distinguish between task-induced or operator-induced workload, and it has been found that it does not distinguish well between similar situations with different workload but constant performance.

Subjective Workload Assessment Technique (SWAT)

The Subjective Workload Assessment Technique (SWAT) considers three individual parameters with three different levels each, giving a total of 27 different combinations. SWAT considers time, mental and stress load at any point. The subject gives a 1 to 3 rating for each type of load, which can then be translated into a workload rating. The SWAT workload scale is highly correlated with the Bedford scale, especially for post-flight situations, where the SWAT scale is applied from video footage of the operator performing the task.

Both SWAT and TLX address the underlying factors behind workload.

2.5.2 The use of workload in this study

The reasons for considering workload are stated below.

1. The requirement to examine the subjective pilot workload for given control laws.
2. To evaluate the perceived workload with different pilots for the same control law.
3. To evaluate the degree of pilot attention available to perform other cockpit tasks.

For the purposes of this study, two primary workload assessment techniques have been chosen. The first is the Bedford scale. This is similar to Cooper Harper, and can therefore be readily understood by pilots. It is simple to administer, and has been shown to correlate very accurately with more sophisticated scales such as SWAT [32]. Therefore this should give an indication of the workload for each of the control laws investigated. The workload measurements are also intended to distinguish between different control law types, where there may be little variation in performance between given control laws, but a large variation in pilot rating or opinion. NASA TLX will be used for this purpose.

Workload should also be able to characterise the effect of the autothrottle on control law performance. Again, there may be significant variation in pilot opinion or rating for a small variation in performance. A measure such as TLX will also distinguish the source of the workload.

Finally, the workload measurement should give an indication of the excess capacity within the pilot which may be used for other tasks which are not represented here, such as radio communications or navigational functions.

Cardiac data, which has often been used to characterise workload, will not be taken for these evaluations. This is because a fixed-base engineering simulator is being used, and therefore there is none of the anxiety associated with actual flight experiments, such as those used in a variable stability aircraft such as the USAF TIFS. Also many of the motion cues which would be present in a moving-base simulator are not present.

According to Hancock [35], prior load profile is a strong moderating influence on workload. Workload is also useful since it offers a window on efficiency, and one that potentially offers information before rather than after the fact. Anyone wishing to use workload measures, particularly subjective responses, must be concerned that there are occasions where an opinion is being expressed that the task is becoming harder while performances are actually improving and vice-versa. Hancock suspects that this is part of the non-linear human response. That is, humans in general, and pilots in particular, use their previous experience and future expectations to scale current events. The fact that these effects are context-specific is most frustrating and is probably due to the nature of the task being performed. For aviation, the hopeful aspect of these findings is that direct association between performance and workload appears mainly in the monitoring tasks, which are becoming more common in contempory cockpits.

Since the subject of Human Factors has now become part of the syllabus for the private pilot's licence, texts have appeared targeted at this group of people. Workload is included in these texts, and a very good description can be found in [36]. This text makes the following key points (page 44).

1. The relationship between workload and performance can be conceived in the shape of an inverted 'U' curve. Human performance at low and high workload levels is not particularly good, and the optimum level lies somewhere in the middle.

2. The human information processing model may help us to determine the source of the overload. It may be that the task is too difficult, i.e. the amount of information which is required to be perceived by the pilot for the decision to be made is too difficult (called qualitative overload), or alternatively there may be too many responses to handle in the time available (called quantitative overload).

Chapter 3

Aircraft Description

3.1 Configuration

The aircraft considered for the purposes of this study is a Generic Regional Aircraft. It is a 100 seat passenger aircraft with a low wing which has twin under-slung engines, and has a conventional tail.

3.2 Simulator Description

The Engineering Simulator used for the primary evaluations was designed and manufactured at British Aerospace Hatfield, but is now located at Avro International Aerospace, Woodford. It is used primarily for engineering development work, some flight crew training and some certification activity.

The simulator is a fixed base device, with a simulation cab which represents a British Aerospace 146 / Avro RJ cockpit. The visual system consists of two outside views per seat, one centre window, and one mounted to the outside of the centre display. The outside view is night, with 8 levels of grey. The navigation fit is a phase II Avro RJ fit, with a EFIS Primary Flight Display, Navigation Displays and servo altimeters on both sides. Height callouts were made at 500, 100, 50, 40, 30, 20 and 10 feet, as well as a glideslope callout at one mile.

The simulations were run on a dedicated DEC VAX4000 computer, using an iteration rate of 50 Hz. Intervention during simulation is possible through a computer terminal mounted in the simulation cab. For the purposes of the evaluation, the aircraft was flown from the left hand seat by the evaluation pilot, with the test administrator sitting in the right hand seat. No flying was performed from the right hand seat.

3.3 Feel System

The cockpit consists of a centre wheel control inceptor, with a fully programmable active feel system, which runs at 500 Hz. A fully programmable active sidestick is also fitted, which runs at about 1000 Hz. The system is able to simulate end-stops, constant loads, damping, friction and spring forces. The individual feel system characteristics are described for the individual control laws in the appropriate section. A constant stick force /displacement gradient was used which is described in appendix B.2.

3.4 Actuator Dynamics and Flight Control System Hardware

Actuators were modelled as simple first order lags. They were assumed to be identical for all configurations evaluated.

The flight control system was assumed to be perfect, and no allowance for failures was made. A proposed flight control system hardware design for this type of aircraft can be found in reference [3].

3.5 Ground Effect Model

The ground effect model used was developed for the baseline aircraft. It consists of increments to the pitching moment and lift force, based on a height schedule. The exact characteristics are confidential, but have been validated by one of the project development pilots.

3.6 Engine Model

Four engine levers are fitted, but only the inner two are used since the aircraft under consideration is a twin. Full engine displays are fitted, with the primary engine display being engine fan-speed (N1), to which power settings were referenced. The engine itself had a simulated Full Authority Digital Engine Control (FADEC) system which is a N1 demand system. The engine N1 demand was generated from the appropriate power lever angle.

3.7 Atmospheric Disturbances

Atmospheric disturbances were available in the model, but not used for these evaluations.

3.8 Flap configuration

The aircraft has a total of five flap positions. These are labelled 0 to 4. Positions 3 and 4 are generally used for approach and landing. Position 2 is generally used for take-off. Only positions 3 and 4 were used for these evaluations.

3.9 Flight Envelope

The aircraft as modelled for development purposes, is an incomplete aircraft model, since many of the non-linearities associated with aircraft such as compressibility effects and extreme non-symmetrical flight have not been considered. In addition, many minor effects have not been modelled due to computing limitations. Therefore the aircraft model used for development is close, but not identical to the complete aircraft model.

The aircraft model has been assumed to be representative up to an equivalent airspeed of 250 knots at sea level, ignoring compressibility. The control laws designed here have considered speeds up to 250 kts. The aircraft has a full flap and gear model. There is also a ground effect model, although this is not used for design purposes.

Chapter 4

Control Law Design

4.1 Basic Aircraft Description

The aircraft under consideration for this study is a twin-engined 100 seat Generic Regional Aircraft, with a design weight of 90,000 lbs, and a mid centre of gravity position. The engines are mounted under the wing, in a configuration similar to a Boeing 737 or Airbus A320.

The principal transfer functions used for the design are given here. DEN is the longitudinal denominator used for all of the transfer functions quoted, and N is the appropriate numerator. The transfer functions may be decoded as follows.

K (a) [ζ,ω]

where,

K is the DC gain, (a) corresponds to a single pole as follows (s+a), and [ζ,ω] corresponds to the complex pair of poles written as $[s^2 + 2\zeta\omega s + \omega^2]$.

An airspeed range of 140 down to 121 knots on the approach is used. Two flap configurations are also used. Flap 3 is a landing flap setting, but is generally used as an approach setting, since flap 4 (full flap) gives more drag, and is therefore used as the final approach flap setting. More detail on the aircraft itself is available in chapter 3.

140 knots, flap 3

$$N^{\gamma}_{\delta e} = K^{\gamma}_{\delta e}(0.0017)[0.2043, 2.5087] \tag{4.1}$$

$$N^{\alpha}_{\delta e} = K^{\alpha}_{\delta e}(-19.0411)[0.0732, 0.192] \tag{4.2}$$

$$N^{\theta}_{\delta e} = K^{\theta}_{\delta e}(0.584)(0.0646) \tag{4.3}$$

$$DEN = [0.5827, 0.8997][0.0253, 0.1496] \tag{4.4}$$

140 knots, flap 4

$$N^{\gamma}_{\delta e} = K^{\gamma}_{\delta e}(0.0206)[0.2015, 2.5005] \tag{4.5}$$

$$N^{\alpha}_{\delta e} = K^{\alpha}_{\delta e}(-19.044)[0.1066, 0.1915] \tag{4.6}$$

$$N^{\theta}_{\delta e} = K^{\theta}_{\delta e}(0.571)(0.0863) \tag{4.7}$$

$$DEN = [0.5547, 0.9401][0.092, 0.140] \tag{4.8}$$

120 knots, flap 4

$$N^{\gamma}_{\delta e} = K^{\gamma}_{\delta e}(0.0038)[0.2102, 2.1687] \tag{4.9}$$

$$N^{\alpha}_{\delta e} = K^{\alpha}_{\delta e}(-16.2492)[0.0950, 0.2232] \tag{4.10}$$

$$N^{\theta}_{\delta e} = K^{\theta}_{\delta e}(0.4701)(0.1097) \tag{4.11}$$

$$DEN = [0.6083, 0.7465][0.0510, 0.1513] \tag{4.12}$$

4.1.1 Lateral Modes

The lateral modes have been described briefly here for completeness.

Roll Mode

Analysis of the aircraft roll mode shows that the inverse roll mode time constant has values between 0.8 s at 120 knots, decreasing to 0.4 s at 240 knots. Again, this is deemed to be suitable for this type of aircraft.

The proposed MIL-STD [37, 38] standard states that the roll mode time constant for a class III aircraft should be less than 1.3 s. For the Generic Regional Aircraft, this requirement is therefore met.

Spiral Mode

Analysis of the aircraft model shows that the spiral mode is always stable, and has an inverse time constant between 0.01 s^{-1} at 120 knots and 0.03 s^{-1} at 200 knots. This is deemed suitable for an aircraft of this type.

Modern fly-by-wire control laws have been programmed so that the pilot is effectively flying an aircraft with zero spiral stability. In other words, the roll inceptor demands roll rate, and the system will hold the roll attitude which is attained when the inceptor is released. Since this aircraft has a stable spiral mode, i.e. it will tend to try to attain a zero roll attitude angle, the unaugmented aircraft may not be suitable for fly-by-wire flight, and a lateral control law may therefore be needed.

Dutch Roll Mode

The Dutch roll damping ratio was found to be approximately equal to 0.06 at 120 knots, increasing to 0.15 at 240 knots. The Dutch roll natural frequency was found to be approximately equal to 1 rad s^{-1} at 120 knots, increasing to 1.5 rad s^{-1} at 240 knots.

4.2 Autothrottle Design

The autothrottle design is based on the use of classical design methods. Unlike many modern autopilots where the required thrust is calculated from a database of aircraft performance and drag data, the autothrottle was designed to use speed error feedback, which is then passed through a PID controller, and the output fed to the engine N1 (fan speed) demand system.

To implement the autothrottle, two different operating modes were designed. The first is a 'Normal' mode, where the speed is held at a demanded value by the autothrottle. The second mode is a 'Take-off' mode, where full power is selected, and maintained until the aircraft passes a pre-determined altitude. This is typically set to 500 feet, and is programmable on the Master Autopilot Control Panel.

In addition, a 'Flare mode' is introduced. This is where the throttles are set to idle when the aircraft passes through a reference height in the landing flare. This height is set to 40 feet for the purposes of the evaluations considered. For this mode to be 'armed', the throttles need to be in the fully aft position since they are non-moving in this implementation.

The autothrottle was designed after analysing the drag characteristics of the aircraft at low level. It was found that the thrust change corresponding to a given pitch change was more or less independent of the current airspeed. In addition, reasonable performance could be obtained by using fixed gains for airspeeds under 200 knots. Therefore a set of gains were designed for the aircraft, and adjustments were made to fine-tune the gains in the Avro and Cranfield Simulators. The structure of the autothrottle is shown in figure 4.1, and the autothrottle gain schedules can be found in appendix B.

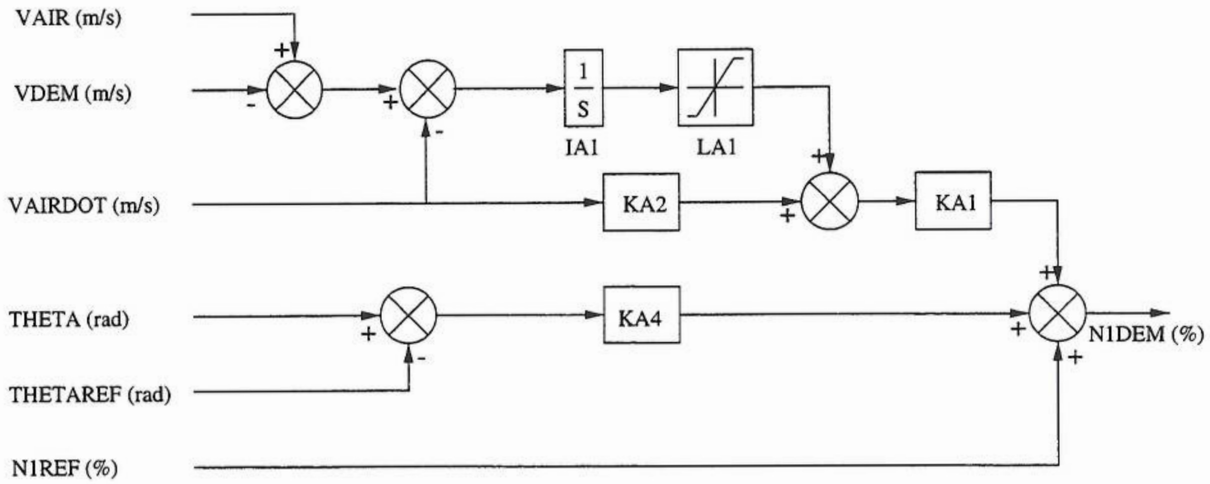

Figure 4.1: Autothrottle conceptual diagram

4.3 Direct Pitch Law

The controllers were initially designed with a limited flight envelope. In order to look at the problems of gain scheduling, it was decided to cover a range of aircraft configurations and speeds. Therefore the control laws were designed to cope with a speed range from approach (120 knots) up to a reasonable up and away speed (250 knots). This would then enable the aircraft to be flown up into the circuit and beyond, even if the complete flight envelope was not evaluated. In addition, both longitudinal and lateral laws were considered, although the lateral laws which were finally used had already been designed and tested. The feel characteristics for this law can be found in appendix B.2.

4.4 Longitudinal Control Law Design Issues

The bandwidth of the unaugmented aircraft is low compared to the requirements specified for level 1 qualities, and this is confirmed by Field [2], who used an almost identical aircraft model. The low bandwidth can be attributed to a low short period mode natural frequency, and this is again confirmed by Field. The short period frequency was increased to 1.5 rad s^{-1} for the approach flight phase at about 120 knots and the aircraft exhibited much-improved handling qualities. Field [2] show that the pitch attitude bandwidth needs to be at least 1.3 rad s^{-1} and the flight path bandwidth needs to be at least 0.65 rad s^{-1} for level 1 characteristics.

Control Anticipation Parameter

CAP is an established criterion which has been frequently used for classical aircraft. The boundaries are well known, but there is some dispute about the lower level 1 value, which is generally considered to be too low, resulting in lower short period natural frequency values. A current level 1 CAP value has been shown to give level 2 flying qualities. This is also confirmed by Field [2].

Analysis of the aircraft was performed for several flight conditions. The value for the CAP for the unaugmented aircraft was 0.188 rad s^{-2}/g. This is towards the lower limit of the current MIL-STD-1797A [18] limits for class III aircraft for the approach and landing phase. Field [2] recommends that the level 1 CAP lower limit should be around 0.5 rad s^{-2}/g. The low value of CAP was primarily due to the low short period mode natural frequency. The short period mode damping was approximately in the middle of the level 1 envelope. When the aircraft was augmented to level 1 characteristics by increasing the short period mode natural frequency to 1.5 rad s^{-2} for the approach flight phase, the value of the CAP increased to 0.7412 rad s^{-2}/g, which is in the middle of the current level 1 CAP envelope, and also higher than Field's recommended lower CAP value of 0.5 rad s^{-2}/g.

For a higher approach speed (160 kts, flap 3), the unaugmented CAP value is 0.205 rad s^{-2}/g, compared with the augmented value of 0.7067 rad s^{-2}/g. The unaugmented aircraft is still therefore at the lower end of the current level 1 CAP envelope, with the short period damping ratio being a little low at 0.55 rad s^{-2}/g. Increasing this to 0.7 rad s^{-2}/g, and increasing the short period mode natural frequency to approximately 2 rad s^{-1} should therefore make the aircraft level 1.

Longitudinal Wheel Forces

The stick force gradients were initially designed to give an initial pitch acceleration of 0.7 deg s^{-2}/lb. For a large aircraft, the recommended value for initial pitch acceleration for unit stick force is between 0.4 and 0.7 deg s^{-2}/lb. Again, with this aircraft it has already been found that 0.7 deg s^{-2}/lb is suitable, and being a small class III aircraft at 90,000 lbs weight (compared to 1,000,000 lbs for a future large transport aircraft), it is likely that a suitable initial pitch acceleration should be towards the higher end of the scale.

Mission Oriented Flying Qualities Requirements

Clearly, one of the most dominant factors in aircraft flying qualities design is the dynamic response of the airframe / flight control system combination, which is strongly related to the aircraft's handling qualities. These handling qualities requirements then tie up with the task and other aspects of the aircraft such as the pilot's displays, and these characteristics are called flying qualities.

The flying qualities requirements are dependent on many factors, but one of the most important is the aircraft mission. It is imperative that the aircraft's flying qualities are designed with the aircraft's mission in mind, since the requirements for the landing task of a large transport aircraft are different to those for a highly manoeuvrable fighter aircraft in the air-to-air combat task. Therefore, Mission Oriented Flying Qualities (MOFQ) have arisen out of the need to be able to tailor an aircraft's flying qualities to the required task.

Modern flight control systems are capable of making an aircraft behave in a very non-conventional manner, conventional being a well-behaved classical aircraft with no augmentation. This results in many different control strategies being developed, of which some are more suitable than others.

The work undertaken here has been done from the viewpoint that control strategies can be made to behave in different ways, and therefore the factors which are relevant to good handling and flying qualities should be extracted, and incorporated into a flight control system design. It should therefore be possible to enable most control strategies to be implemented, and behave reasonably well, although there will still be limitations imposed by the strategy itself which may differentiate between the different strategy.

Therefore the factors which are 'strategy independent' have initially been covered, and then these key factors have been incorporated into the individual strategies. The definition of the task is fundamental to the evaluation of aircraft handling qualities. Suitable task definitions can be found in appendix C of [13].

Flare Requirements

The flare requirements are different to the approach requirements, since the speed and angle of attack are changing in the flare, and it is therefore a non-steady flight condition. In addition, ground effect plays a major part, indeed in aircraft such as the Boeing 747 and Concorde, it is quite possible to land the aircraft without any flare at all since ground effect will cushion the aircraft successfully. Also, for situations such as carrier landings and a McDonnell Douglas C-17 backside approach for a short landing, the pilot makes no flare, instead relying on the aircraft to absorb the high rate of descent.

In conventional civil aircraft, the pilot has to make an exponential rearwards longitudinal inceptor movement in order to land the aircraft. This is due to the fact that the speed is decreasing at a reasonably constant rate once the power has been removed, and this results in an exponential angle of attack requirement if level flight is to be maintained. Field [30] states that monotonic forces in the flare are preferred since they give less of a floating tendency. All conventional non-fly-by-wire aircraft have monotonic control forces in the flare, and this has been retained in fly-by-wire aircraft through a variety of means. This is done to ensure that the aircraft is operated outside the deadband region of the stick, and it means that the pilot does not have to adopt a stick pumping technique, i.e. rapidly moving the stick backwards and forwards over the mid-point.

Field [30] found that for a fixed-base evaluation, an angle command control law gives ratings which are approximately 1 Cooper Harper Rating point better than a comparable rate command system. Rate command systems are also generally rated better in a fixed-based ground simulator than in an in-flight simulator. Current fly-by-wire aircraft retain this conventional flare characteristic by either making the aircraft speed stable, and therefore requiring a monotonic stick input to increase the angle of attack sufficiently, or adopting an angle command characteristic through an attitude command law. Attitude has been found to be more suitable than flight path since in the flare the flight path is more or less constant, therefore requiring a step change in flight path, i.e. non-conventional, while the aircraft attitude increases in something like an exponential / rate manner to reflect the exponential angle of attack requirement.

Energy Awareness

The Federal Aviation Administration Human Factors Team report on the interfaces between flight crews and modern flight deck systems [39] reports on many issues relevant to modern transport aircraft. Although much of the report is devoted to flight management systems, a part of it is devoted to piloted flight. One situational awareness recommendation (Recommendation SA-1) states that :

> The FAA should require operators to increase flight crews' understanding of and sensitivity to maintaining situational awareness, particularly:
>
> - Mode and airplane energy awareness issues associated with auto flight systems (i.e., autopilot, autothrottle, flight management systems, and fly-by-wire flight control systems);
> - Position awareness with respect to the intended flight path and proximity to terrain, obstacles, or traffic; and
> - Potential causes, flight crew detection, and recovery from hazardous pitch or bank angle upsets while under autopilot control (e.g., wake vortex, subtle autopilot failures, engine failure in cruise, atmospheric turbulence).

The first two are of prime concern here. Whereas the pilot used to be required to be aware of the airspeed, this states that he/she must also be aware of the aircraft's energy state. The report also states that

> Examples of items that flight crews should be made aware of include ...
>
> (3) Situations that can result in hazardously low energy states when using the control wheel steering autopilot mode on airplanes with a conventional control system or during manual flight of airplanes with a fly-by-wire control system when the particular implementation of these systems results in neutral longitudinal speed stability (i.e., stick force versus speed)."

This report also considers mixed mode flying. This is where elements of automatic and manual control are combined, such as an approach flown manually with the autopilot engaged. Some aircraft operators do perform this type of flying while others do not advocate it. Some of the associated risks are that it masks the energy state of the aircraft. An autothrottle can be destabilising in a conventional aircraft (non fly-by-wire) due to the location of the engines, but it is perfectly acceptable with a fly-by-wire system based on an attitude or manoeuvre demand control law since the destabilising effect is removed by the flight control system.

These arguments are very important. They state that the following issues must be considered when evaluating control laws.

- Pilot energy awareness

- Pilot speed awareness
- The use of the autothrottle for different control laws
- The retention of speed stability with the autothrottle engaged.

Speed Stability

The control characteristics of a conventional aircraft is angle of attack demand in the long term. This means that the aircraft is trimmed to a given angle of attack, and any variation from this trimmed value (for non-power assisted controls) is felt by the pilot through tactile feedback from the stick. This characteristic is retained in conventional civil aircraft with power assisted controls through the use of a 'Q-pot', which generates a stick force gradient which is dependent on the difference between a trimmed value and the actual dynamic pressure. Since dynamic pressure is inversely proportional to the required angle of attack to maintain a given amount of lift with a constant wing area, the pitch inceptor is still working as an angle of attack demand controller. Therefore the required stick force to generate a certain airspeed change decreases as the initial airspeed increases as the required angle of attack change is less. Limits on the speed change per stick force are placed on the force characteristic; a Federal Airworthiness Requirement (FAR 25.173) [40] is a requirement for the average stick force gradient to be at least 1 lb force for 6 knot change in speed. If the aircraft has a wide speed range, this may cause unacceptably high stick force gradients in the flare in order to meet the stick force gradient at V_{MO}. Therefore the stick force to elevator gearing may vary over the flight envelope.

FAR 25 [40] also places other requirements on the aircraft speed response in section 25.173 (static longitudinal stability). The speed response must fulfil certain criteria with respect to the nature of the speed response. For example, the airspeed is permitted to stabilise at a non-trimmed value as long as the pilot attention required to restabilise the speed at the desired value is not excessive. Therefore there may be a conflict for non-conventional response types where there is no inherent static stability.

Moorhouse [31] considers the apparent effect of losing speed stability as the pilot performs a tight glideslope hold task. The classical view of aircraft dynamics is an open loop type analysis, where the phugoid and short period are two significantly different modes. He describes how the phugoid mode is modified by the aircraft / pilot closed loop combination to an aperiodic mode, which gives the appearance of losing speed stability. This occurs because the oscillatory phugoid has the effect of returning the speed error to zero, while the aperiodic mode will never reach zero. Therefore it is inferred that aggressive pitch control by a pilot to control the glideslope will cause the appearance of a lack of speed stability, and therefore could induce or require more corrective actions in the pitch axis. He also demonstrates that the major ambiguity in piloting cues is the coupling between airspeed and flight path responses. He therefore postulates that a more effective control law design could be made by decoupling the two responses, with airspeed being the reference instead of the angle of attack, and the results were validated in a fighter aircraft under a variety of conditions.

Other factors have been stated from work performed in the past. The characteristics of the phugoid are important in the task of speed control. The phugoid motion is a long period mode, of the order of 30 to 60 seconds time period, and for a conventional aircraft it consists of a sinusoidal variation in speed and pitch attitude. It is usually lightly damped since the damping arises through the change in drag with speed, and low drag configurations, which are desired for economic reasons tend to have very lightly damped phugoids.

Chalk [28] found that increasing the phugoid natural frequency (ω_{ph}) resulted in increased stick force feel for airspeed deviations. Also, no significant improvements were made to handling for a phugoid damping ratio (ζ_{ph}) greater than 0.15. Holleman [41] states that the phugoid damping increases as the drag to lift ratio increases, i.e. the aircraft is well on the frontside or backside of the drag curve. However, civil aircraft are generally flown along the approach near the minimum drag speed, i.e. at the bottom of the drag bucket, and therefore the phugoid damping ratio is about as low as it ever goes. Holleman also states that the phugoid is very controllable under Visual Flight Rules (VFR) but not under instrument conditions, which may cause problems if the aircraft has to be flown manually under Instrument Flight Rules (IFR). Rynaski [42] states that a phugoid-like response is crucially relevant in longitudinal flying qualities, especially the angle of attack (α), speed and pitch attitude (θ) residues in the phugoid mode. It is likely that the flight path residue is also important when the aircraft nears the ground - in the Sioux City DC-10 accident, the aircraft was near the bottom of the phugoid when it hit the ground.

For a classical aircraft, increasing the speed feedback slightly increases the short period frequency and slightly reduces the short period damping. The effect of the feedback on the two characteristics is similar. However, the main noticeable effect is in the phugoid stabilising. A small speed feedback to elevator may have a noticeable effect on the phugoid mode, but no discernible effect on the short period mode.

As the speed feedback gain increases, the phugoid poles are drawn towards the speed to elevator complex zeros. This should be the same for non-conventional response types, where a new long term mode will be formed.

Other speed requirements are the attention required for manual speed control. In addition, the effect of the aircraft autothrottle must be addressed. An autothrottle should not compensate for poor speed characteristics of the aircraft, and the associated pilot situational awareness issues must also be addressed. Speed control problems can contribute to a large component of the degraded handling qualities ratings, even when there are no longitudinal pitch control problems [14].

Pilot Cues

The pilot ratings were degraded for cases where the pilot was located on or behind the centre of rotation.

During a study conducted using a 1,000,000 lb aircraft, it was found that the pilot ratings were degraded for cases where the pilot was located on or behind the centre of rotation. In addition, the evaluation pilots applied a less demanding manoeuvrability than with other studies. For this class of aircraft, the pitch attitude bandwidth appears to be 1.5 rad s^{-1}. The degradation caused by time delay was therefore lower with this type of aircraft due to the lower bandwidth. Therefore present day MIL-F-8785C time delay limits appear to be conservative in light of this.

When the pilot position if forward of the CG, the pitch acceleration response provides an earlier cue to the pilot of the aircraft responding. This cue is delayed by the control system delay, but not by the lag associated with the short period mode.

There were problems with the pilot seated behind the centre of rotation. This was due to the initial normal acceleration kick, and the height response at the pilot's station, which especially caused problems in the flare. The worst configurations were referred to as very sluggish and delayed, and resulted in PIO's many times, with the lateral control task being completely neglected. Precise control of sink rate near touchdown was often impossible.

Ride Quality Requirements

Weingarten and Chalk [14] found the pitch rate configurations were preferred to the angle of attack demand configurations, especially with the pilot behind the centre of rotation. This was due to the lower turbulence response, attitude hold feature and level turn capability without pitch inputs.

Time Delays

The degradation due to the effects of time delay was 1-3 CHR for time delays from 0.14 to 0.3s. It was thought that this reduction in degradation was due to the pilots applying lower levels of required agility due to the larger aircraft. One pilot said he used a precognitive attitude technique, relying on memorised attitudes in the approach and flare which give acceptable sink rates and touchdowns. With this technique, the pilot is less sensitive to time delays in the command path. Part of the increased tolerance to time delays is the normal acceleration response, which gives a cue that the aircraft is responding.

Turn Coordination

Despite the fact that the lateral handling qualities are not being specifically evaluated, it is important that the flight control laws are as representative as possible of the command concepts used so that they give each concept a fair chance. Therefore turn coordination was designed for each control law. In the case of pitch rate command laws, it consisted of calculating the required body pitch rate to coordinate the turn, so that the pilot did not have to perform the coordinating action himself. This was tested on the Cranfield engineering simulator, and the results were successful. For the normal acceleration control laws, the turn coordination was effected by calculating the required load factor required to coordinate the turn at a specific angle of bank, and then feeding this into the longitudinal control laws. For the C* control laws, the coordination was performed by a mixture of both methods.

Fly-by-wire civil aircraft which have turn coordination tend to only coordinate turns up to certain angles of bank. This is so that the pilot is discouraged from exceeding specific attitudes since he would have to hold significant control forces to maintain these attitudes. These features were not explicitally modelled since the pilots were not achieving the high bank attitudes (say above 45 degrees) to require these systems. However, the inclusion of such a system would be a reasonably straightforward task.

4.5 Law Independent Design Criteria

In order to design the longitudinal control laws, the following law independent design criteria were developed.

1. The ratio of the initial pitch acceleration to final normal acceleration (i.e. a GCAP or CAP value) shall be set to 0.6 deg s^{-2}/g.
2. The short term mode natural frequency is proportional to the airspeed, as with a classical aircraft.
3. The short term mode damping ratio is set to 0.7.
4. The initial pitch acceleration shall be 0.6 deg s^{-2}/lb.
5. The pitch attitude dropback ratio (dropback divided by steady pitch rate) shall be 0.5 at 120 knots, 0.4 at 140 knots and so on until it reaches its minimum value of 0 at 220 knots.
6. No control law shall be rate demand in the flare. In the event of this, the law shall be modified to incorporate a flare law to give attitude-like properties.

4.6 Longitudinal Control Laws

This section describes the longitudinal control laws which have been designed for evaluation in this study, along with the design process used to obtain them.

4.6.1 Augmented Aircraft (Angle of Attack)

Most current transport aircraft do not have fly-by-wire systems, and therefore are conventional angle of attack command systems. This control law is designed to examine this response type. Therefore the basic aircraft has been augmented to produce level 1 characteristics for the approach and landing. Some aircraft do have longitudinal stability augmentation systems, such as pitch dampers, and therefore this law replicates one of these.

Analysis of the unaugmented characteristics show that the aircraft is generally conventional in nature, with the short period frequency around 1 rad s^{-1}, and with a damping ratio (ζ_{sp} of around 0.52 - 0.6). Both of these values are lower than desired, and therefore the controller strategy is to increase the damping through pitch rate feedback to elevator, and the short period mode natural frequency through angle of attack feedback to elevator.

This control law was designed with two main purposes in mind. The first was to augment the short period mode frequency to a level 1 value. Experience from Field's work [2] showed that a value of 1.5 rad s^{-1} was suitable for the approach and landing phase, and this also gave a CAP value of approximately 0.6 in the approach configuration. This was therefore augmented using angle of attack feedback. The short period damping was also increased to the required value using pitch rate feedback.

Both of the angle of attack and pitch rate feedbacks were scheduled with speed. In addition, the angle of attack feedback gains were scheduled with aircraft configuration. The phugoid mode characteristics are modified by the feedbacks. Before augmentation, the phugoid had level 1 characteristics, and these were retained after the augmentation.

Since this control law was designed to simply augment the characteristics of the short period mode to level 1 values, no account was taken of dropback explicitly in the design process.

Controller Structure

The controller structure can be seen in figure 4.2. It can be seen that three command gains are used, and are listed as follows.

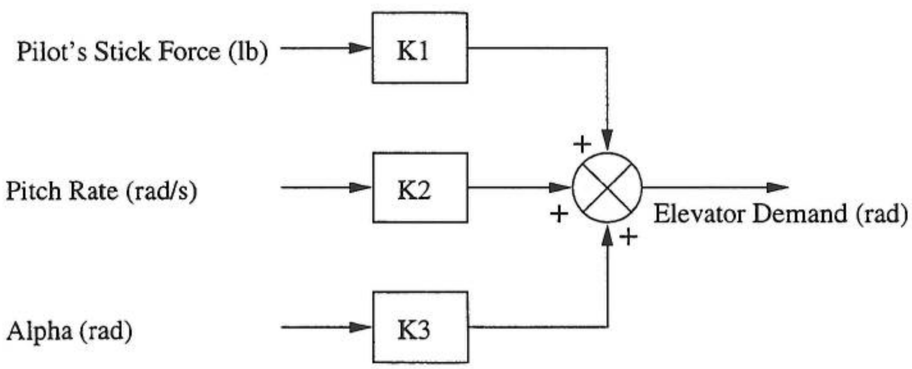

Figure 4.2: Law 1 conceptual diagram

K3

1. K1 - Angle of attack to elevator gain. This gain was used to increase the short period mode frequency, and was scheduled with respect to speed and aircraft configuration. The short period mode natural frequency was set at 1.5 rad s^{-1} at 120 knots, increasing by 0.25 rad s^{-1} for each subsequent 20 knots.
2. K2 - Pitch rate to elevator gain. This gain was used to increase the short period mode damping, and it was scheduled with respect to airspeed. The short period mode damping ratio was set at 0.7 for all of the configurations considered.
3. K3 - Pilot's stick force to elevator gain. Due to the nature of the feel characteristics, the feel system required gain scheduling to allow for speed variations. This was carried out in the classical form by using a basic stick force gradient, coupled with a Q-pot component.

K1

The control gains can be found in appendix B.3.

Design Process

The control law design process is quite simple for this control law. It has been deliberately designed with simplicity in mind so that it could possibly be regarded as the cheapest option if augmentation is required.

The process is as follows, and must be repeated for each individual design case.

1. Augment the short period mode natural frequency with angle of attack feedback.
2. Augment the short period damping with pitch rate feedback.
3. Select command gain.

4.6.2 Pitch Rate

Pitch rate command laws originated in fighter aircraft since they provide excellent pitch pointing characteristics by their nature, and they are also semi-conventional, since a classical aircraft behaves in a pitch rate manner in the short term. Pitch rate control laws generally form the basis of the low speed control laws for current fighter aircraft, with some additional elements to artificially induce speed stability.

In addition, the McDonnell Douglas C-17 uses a pitch rate command system as its 'frontside law', with the backside control law being a conventional angle of attack command system. Also, C* laws, which the Boeing 777 has based on consist of primarily pitch rate like characteristics at approach speeds.

The C-17 uses conventional control sticks to provide the primary pilot inputs. However, fighter aircraft using pitch rate control laws or a derivation of them use either sidesticks in the case of the F-16, or centre sticks in the case of Eurofighter and EAP. Pitch rate control laws are particularly suited to sidestick applications since there is no requirement to trim the aircraft due to the zero speed stability. Trimming is possibly more difficult to perform with a sidestick due to the low deflection levels and lower force levels, possibly leading to a more open loop trimming strategy.

Controller Structure

The controller structure can be seen in figure 4.3. It can be seen that eight command gains are used, and are listed as follows. This controller structure is used for all of the generic pitch rate laws, and therefore some of the gains may be set to zero.

1. K11 - Overall controller to elevator gain. Increasing K11 has the effect of increasing the natural frequency of the short term mode, plus increasing the damping ratio of the long term mode.

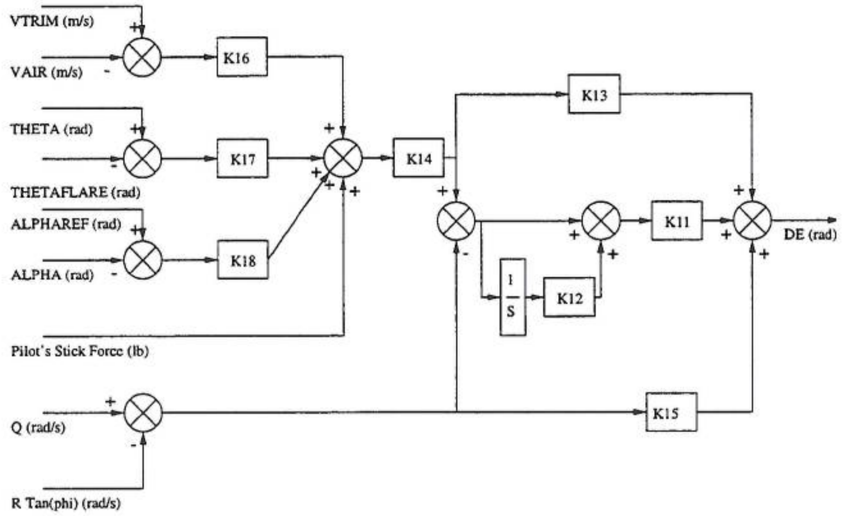

Figure 4.3: Laws 2, 3 and 8 conceptual diagram - pitch rate demand system

2. K12 - Integrator to Proportional controller gain. This gain was used to increase the short term mode natural frequency and decrease the short term mode damping.

3. K13 - Feedforward gain. This gain is used to modify the dropback characteristics of the initial response. Increasing the dropback has the effect of increasing the 'peakiness' of the initial pitch rate response. It also controls the location of the controller zero which is found in all of the elevator transfer functions for a given value of K12. This enables the flight path response to be approximated to K/s in the crossover region, which corresponds to a zero placed around the same location as the $1/T_{\theta_2}$ location.

   The location of the zero has the effect of altering the dropback for all other gains fixed. Increasing the value of the K13 gain increases the dropback as the zero introduced by the controller decreases in frequency, although whether these two are connected is unknown. Certainly, increasing the initial pitch rate response increases the dropback, and this initial response is tied to the value of the feedforward.

4. K14 - Command gain. This is used to control the magnitude of the response to the pilot's input. Due to the nature of the feel characteristics, the feel system required gain scheduling to allow for speed variations. This was carried out in the classical form by modifying the basic stick force gradient and the actual command gain itself.

5. K15 - Damping component. This gain is used to control the short term mode damping ratio. Note that this gain is redundant, but has been included since it simplifies the design process.

6. K16 - Airspeed error to stick force gain. This gain generates a stick force dependent on the airspeed error calculated from the value referenced from the trim wheel, and the current airspeed. This gain is only set to a non-zero value when airspeed stability is required.

7. K17 - Flare law gain. This gain is used to give attitude like characteristics in the flare, and is only set to a non-zero value when the flare law is active.

8. K18 - Angle of attack error to stick force gain. This gain is used to give angle of attack stability. It generates a stick force depending on the size of the angle of attack error. The size of this gain was determined from the required airspeed error to stick characteristic, and a value of 6 knots per pound stick force was initially selected. This value was used since a higher value gives excessive dropback, which it is not possible to correct for using the feedforward gain or a prefilter.

The four gains K11, K12, K13 and K15 may be replaced with three gains, since it is possible to demonstrate that K15 is redundant. However, it has been included in the design process since it makes the design process easier if the K12 gain is fixed at some nominal value, and then the other gains are designed around that fixed value. If the gain K15 is set to zero, then the other gains will have to be modified to account for this, but the modifications are easily determined.

Design process

The control law design process is relatively straightforward for this control law. The process is as follows, and must be repeated for each individual design case. If speed stability using speed feedback is required then the speed error to stick force, gain K16, must be set. If speed stability using angle of attack feedback is required, then the required angle of attack to stick force gain must be set, gain K18. If angle of attack speed stability is required, then gain K18 must be set during the design process for gains K11-15 since it will have a significant effect on the closed loop dynamics.

1. Decide on the required short term mode characteristics.
2. Decide on the value for the gain K12.
3. Augment the short term mode natural frequency with the gain K11.
4. Augment the short term mode damping ratio with pitch rate feedback, gain K15.
5. Repeat the previous 2 steps until the characteristics are suitable.
6. Select the required dropback using gain K13.
7. Select command gain using K14.
8. Iterate if necessary.

If a flare law is required then the reference height and the value for the gain K17 must be decided. For all other cases, the gain K17 is set to zero. The flare law is only required for a pure pitch rate demand system.

It was found that gain schedules were required for the majority of the control gains for the pure pitch rate law, with the exception of K12, which was deliberately kept fixed in order to facilitate the design process. K11 and K13 are scheduled with speed and aircraft configuration, and K14 and

K15 are scheduled with speed alone. K16 is used to give speed stability, and is set to zero for this control law. K17 is used for the flare law, and has a constant value during the period when the flare law is armed.

The gain schedules may be found in appendix B.4

Flare Law

Due to the nature of this response type, it has non-monotonic stick forces in the flare. Field showed that this is unsuitable [2]. In addition, current aircraft which would exhibit pitch rate type responses use a modified law to enable the pilot to use monotonic forces in the flare.

Therefore a law was designed which memorised a reference pitch attitude at a certain height (initially set for 40 feet), and then summed the difference between this pitch attitude value and the current pitch attitude with the pilot's demand. This produced a control system which required the pilot to hold a certain pitch force in the flare which increased as the required attitude increased. Therefore monotonic forces increased. The gain used to do this K17 is set to 60 lbs/rad.

4.6.3 Pitch Rate with Speed Feedback

This law is essentially identical to the pitch rate law previously described, except that speed error feedback is employed to artificially induce speed stability. This type of law is essentially untried, although it exists in similar forms (some combat aircraft employ angle of attack error feedback to generate a positive static margin.

Due to the speed feedback, no specific flare law is needed. If the aircraft is trimmed at an approach speed of, say, 121 knots, the pilot will have to hold the stick back for the aircraft to stabilise at a lower speed for a constant pitch attitude. Therefore the fact that speed is fed back to the demand generates a conventional flare law, with the required longitudinal stick input required during the flare being something like a monotonic ramp input.

This law is designed in the same way as the pure pitch rate law. The final stage in the design process however is to decide on the speed feedback gain. No problems were experienced during the design process for the derivation of the speed feedback gain with the system becoming unstable. The same can not be said for the normal acceleration control law. A fuller explanation of the effects of feeding back speed can be found in section 2.2. In addition, no flare law is required for the reasons just mentioned, and therefore the K17 gain was set to zero. The full gain schedules can be found in appendix B.4.

4.6.4 Pitch Rate with Angle of Attack Feedback

This law is essentially identical to the pitch rate law previously described, except that angle of attack error feedback is employed to artificially induce speed stability. This type of law is essentially untried, although it exists in similar forms (some combat aircraft employ angle of attack error feedback to generate a positive static margin.

Due to the angle of attack feedback, no specific flare law is needed. If the aircraft is trimmed at an approach speed of, say, 121 knots, the pilot will have to hold the stick back for the aircraft to stabilise at a lower speed for a constant pitch attitude. Therefore the fact that angle of attack is fed back to the demand generates a conventional flare law, with the required longitudinal stick input required during the flare being something like a monotonic ramp input.

This law is designed in the same way as the pure pitch rate law. However, the first stage in the design process is to decide on the angle of attack to stick force gain. In addition, no flare law is required for the reasons just mentioned, and therefore the K17 gain was set to zero. This control law has gain schedules which are scheduled with speed. The full gain schedules can be found in appendix B.7.

K18

4.6.5 C*

The C* control law was initially designed as a fighter law for a pitch pointing task. It is characterised by the fact that the pilot demands a blend of pitch rate and normal acceleration. This blend is determined by a crossover velocity, which is defined as the velocity where the pilot's perception of normal acceleration and pitch rate are the same. At low speeds, the C* control law behaves in a pitch rate manner, and at high speeds, it behaves in a normal acceleration manner.

It has often been said that the Airbus A320, A330 and A340 use C* as their primary control law. This is not pure C* as proposed by Tobie and Elliot [43], but a different blend of normal acceleration and pitch rate, and in practice, any blend of normal acceleration and pitch rate is generally referred to as a C* control law. In practice, the Airbus aircraft just mentioned have manoeuvre demand characteristics, where the pilot's pitch inceptor is used to demand something like normal acceleration of flight path rate, and are perhaps closer to the normal acceleration control laws designed here.

The Airbus aircraft use sidesticks with their C* law, and this is particularly suitable due to the rate-like properties of the law. No trimming is required for C* since this law has zero speed stability, although this can be modified with C*U. A flare law is also required due to the pitch rate characteristics at low speed. For the A320, this is done by the system putting in a 2 degree nose down pitch demand over 8 seconds, so that the pilot needs to hold the sidestick rearwards to maintain attitude. For the A330 and A340, the system has been modified so that speed feedback from a reference value is used, and therefore progressively increasing amounts of back sidestick are required as the aircraft slows down.

Design Process

The design process used for the C* command law at low to medium speeds is essentially identical to the process for the pitch rate control law. It can be characterised by the following steps.

1. Select the required value for the ratio of normal acceleration to pitch rate for the derivation of the 'C*' value.
2. Decide on the initial value of the I/P ratio for the integrator component of the controller, gain K22.
3. Obtain the desired short term mode frequency and damping from adjusting the two primary controller gains, gains K21 and K22. In this case it is necessary to obtain the desired short term mode characteristics by modifying these two gains since the pure pitch rate gain, K15, which was included with the pitch rate controller is not present.
4. Set the pitch attitude dropback at the required value using the feedforward gain, K23.
5. Set the command gain using the required value for the initial pitch acceleration, K24.

The controller structure can be seen in figure 4.4. It can be seen that eight command gains are used, and are listed as follows.

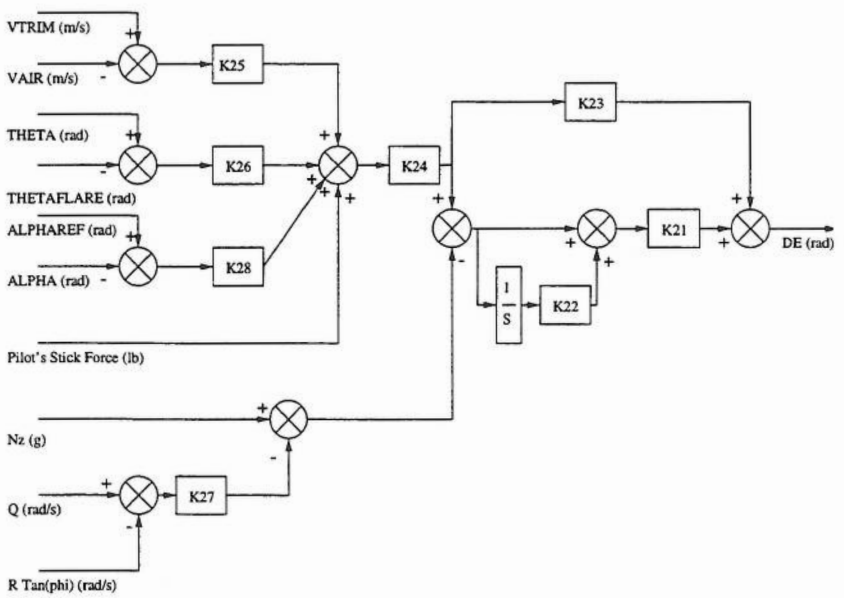

Figure 4.4: Laws 4, 5 and 9 conceptual diagram - C* demand system

1. K21 - Overall controller gain. This gain increases the natural frequency of the short term mode. There is also a marked effect on the long term response.
2. K22 - Integrator to proportional controller gain. This gain increases the frequency and reduces the damping ratio of the short term mode.
3. K23 - Feedforward gain. This gain is used to modify the dropback characteristics of the control law.
4. K24 - Command gain. This gain is used to determine the magnitude of the aircraft's response to a pilots inputs. This gain requires scheduling with airspeed.

5. K25 - Airspeed error to stick force gain. This gain generates a stick force dependent on the airspeed error calculated from the value referenced from the trim wheel, and the current airspeed. This gain is only set to a non-zero value when airspeed stability is required.

6. K26 - Flare law gain. This gain is used to give attitude like characteristics in the flare, and is only set to a non-zero value when the flare law is active.

7. K27 - C* blend gain. Since C* is a blend of pitch rate and normal acceleration, the blend must be determined. For the purposes of this law, the classical C* value of 12.4 g/rad s^{-1} was used.

8. K28 - Angle of attack error to stick force gain. This gain is used to give angle of attack stability. It generates a stick force depending on the size of the angle of attack error. The size of this gain was determined from the required airspeed error to stick characteristic, and a value of 6 knots per pound stick force was initially selected. This value was used since a higher value gives excessive dropback, which it is not possible to correct for using the feedforward gain or a prefilter.

It was found that gain schedules were required for most of the control gains. K22 is scheduled with speed and aircraft configuration, and K21 and K23 are scheduled with speed alone. K25 is used to give speed stability, and is set to zero for this control law. K26 is used for the flare law, and has a constant value during the period when the flare law is armed. The value of the C* blend gain, K27, is set to 12.4 s, which is the value for classical C*. This ratio can be modified if necessary. The gains may be found in appendix B.5.

Flare Law

Due to the pitch rate like response characteristics of this law at low speed, a flare law was introduced in the same way as the flare law for the pitch rate command system.

4.6.6 C* with Speed Feedback

This law is essentially identical to the C* law previously described, except that speed error feedback is employed to artificially induce speed stability. This type of law is essentially untried, although it exists in similar forms (some combat aircraft employ angle of attack error feedback to generate a positive static margin. Again, as with the pitch rate with speed feedback law, no specific flare law is needed.

This law is designed in the same way as the pure C* law. The final stage in the design process however is to decide on the speed feedback gain. No problems were experienced during the design process for the derivation of the speed feedback gain with the system becoming unstable. The same can not be said for the normal acceleration control law. A fuller explanation of the effects of feeding back speed can be found in section 2.2, and the full gains for this law may be found in appendix B.5.

4.6.7 C* with Angle of Attack Feedback

This law is essentially identical to the C* law previously described, except that angle of attack error feedback is employed to artificially induce speed stability. This type of law is essentially untried, although it exists in similar forms (some combat aircraft employ angle of attack error feedback to generate a positive static margin. Again, as with the pitch rate with angle of attack feedback law, no specific flare law is needed. Again, this law is designed in the same way as the pure C* law. However, the first stage in the design process is to decide on the angle of attack to stick force gain. The full gains for this law may be found in appendix B.8.

4.6.8 Normal Acceleration

A normal acceleration control law is where the pilot's pitch inceptor demands a specified load factor. This is essentially to flight path rate, and therefore this type of law is often referred to as a flight path rate command, flight path angle hold. It is non-conventional since this type of law has neutral speed stability.

This type of control law is generally used by modern fighter-type aircraft such as EAP for combat tasks, since studies have shown that the pilot is essentially sensitive to normal acceleration or load factor at high speed or in combat, with respect to his pitch inceptor input. It is also used by the Airbus A320, A330 and A340 as their primary flight control law, with modifications for the flare. The Airbus aircraft use sidesticks, but combat aircraft can use either side or centre sticks with this law.

Due to the rate-like characteristics, a separate flare law is needed to preserve monotonic stick forces in the flare.

Design Process

The design process comprises the following steps.

1. If speed stability using speed feedback is required then the speed error to stick force, gain K36, must be set. If speed stability using angle of attack feedback is required, then the required angle of attack to stick force gain must be set, gain K38. If angle of attack speed stability is required, then gain K38 must be set during the design process for gains K31 to K35 and K39 since it will have a significant effect on the closed loop dynamics.
2. Select the desired short and long term modal properties.
3. Decide on the I/P gain schedule for the integrator component of the controller.
4. Select the appropriate overall controller gain to give the required short term mode frequency.
5. Obtain the desired short term mode and long term mode damping from adjusting the gains K33 and K39. Increasing the value of gain K33 will increase the short term mode damping

ratio only. Increasing the value of K39 increases the value of both the short and long term mode damping ratios. This is due to the fact that K39 gives both pitch rate feedback and integral pitch rate feedback, which is similar to pitch attitude feedback, and pitch attitude feedback traditionally increases the damping of the long term mode. Pitch rate feedback to elevator gain. This gain is required since pitch rate is the only effective way of increasing the short term mode damping.

6. Set the pitch attitude dropback at the required value using the feedforward gain.

7. Set the command gain using the required value for the initial pitch acceleration.

The controller structure can be seen in figure 4.5. It can be seen that nine command gains are used, and are listed as follows.

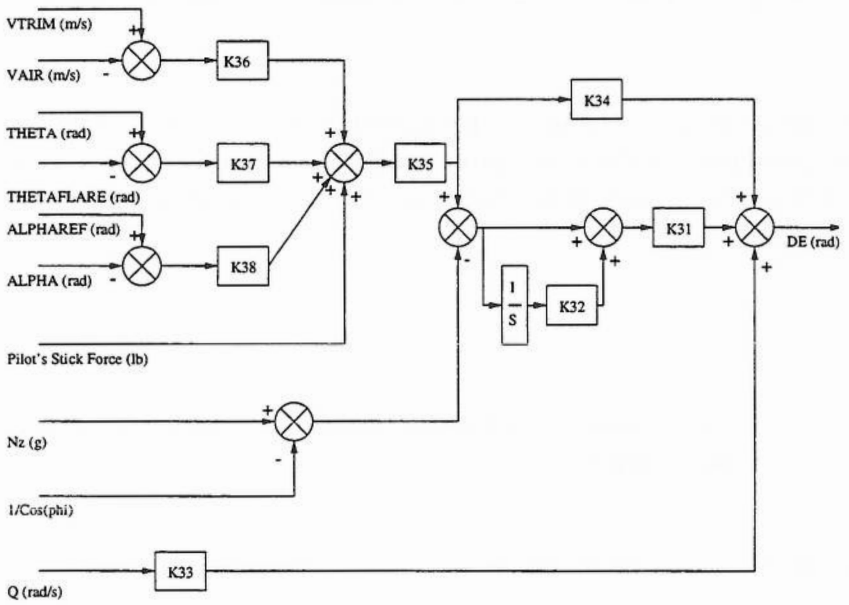

Figure 4.5: Laws 6, 7 and 10 conceptual diagram - normal acceleration demand system

1. K31 - Overall controller gain. This gain increases the natural frequency of the short term mode. There is also a marked effect on the long term response.

2. K32 - Integrator to proportional controller gain. This gain increases the frequency and reduces the damping ratio of the short term mode.

3. K33 - Pitch rate to elevator gain. This gain is used to provide short term mode damping.

4. K34 - Feedforward gain. This gain is used to modify the dropback characteristics of the control law.

5. K35 - Command gain. This gain is used to determine the magnitude of the aircraft's response to a pilots inputs.

6. K36 - Airspeed error to stick force gain. This gain generates a stick force dependent on the airspeed error calculated from the value referenced from the trim wheel, and the current airspeed. This gain is only set to a non-zero value when airspeed stability is required.
7. K37 - Flare law gain. This gain is used to give attitude like characteristics in the flare, and is only set to a non-zero value when the flare law is active.
8. K38 - Angle of attack error to stick force gain. This gain is used to give angle of attack stability. It generates a stick force depending on the size of the angle of attack error. The size of this gain was determined from the required airspeed error to stick characteristic, and a value of 6 knots per pound stick force was initially selected. This value was used since a higher value gives excessive dropback, which it is not possible to correct for using the feedforward gain or a prefilter.
9. K39 - Pitch rate to controller gain. This gain was used to assist with the damping of the short and long term modes.

It was found that gain schedules were required for most of the control gains. Gains K31, K32, K33, K34 and K35 all required speed schedules. Of the other gains, K36 is used to give speed stability, and is set to zero for this control law. K37 is used for the flare law, and has a constant value during the period when the flare law is armed.

Flare Law

Due to the rate like response characteristics of this law, a flare law was introduced in the same way as the flare law for the pitch rate command system.

4.6.9 Normal Acceleration with Speed Feedback

In the same way that a pitch rate with speed feedback is an extension to a pure pitch rate law, normal acceleration with speed feedback is an extension to a pure normal acceleration law. Speed stability is introduced by feeding back a speed error, or the difference between the current airspeed and a reference value set by the pilot using the trimmer, in parallel with the pilot's demands. Therefore for the pilot to maintain an 'off-reference' value, he needs to hold in a specified stick force. The Boeing 777 uses a Nz-U law, and the A330 and A340, which have normal acceleration laws use speed feedback in the flare to permit monotonic stick forces to be used, which is effectively Nz-U.

This law is designed in the same way as the pure normal acceleration law. The final stage in the design process however is to decide on the speed feedback gain. The calculation of this gain was found to be a problem at high speed, the law behaves in a normal acceleration like manner, and it was found that the maximum permitted value of the speed error feedback gain was drastically limited so that the controi forces required to hold a specified speed error were extremely light. This questions the usefulness of having the speed feedback present since it is there to 'remind' the pilot when he is flying at an off-trim speed through tactile feedback of stick forces. A fuller explanation of the effects of feeding back speed can be found in section 2.2. In addition, no flare law is required for the reasons just mentioned, and therefore the K37 gain was set to zero. The control gains may be found in appendix B.6.

4.6.10 Normal Acceleration with Angle of Attack Feedback

In the same way that a pitch rate with angle of attack feedback is an extension to a pure pitch rate law, normal acceleration with angle of attack feedback is an extension to a pure normal acceleration law. Speed stability is introduced by feeding back an angle of attack error, or the difference between the current angle of attack and a reference value set by the pilot using the trimmer, in parallel with the pilot's demands. Therefore for the pilot to maintain an 'off-reference' value, a specified stick force needs to be held. No aircraft explicitally uses a $Nz\alpha$ law.

This law is designed in a similar way as the pure normal acceleration law. However, the initial angle of attack gain must be decided beforehand since angle of attack feedback has a significant effect on the short term dynamics. The required angle of attack gain can be decided in several ways. The overall response characteristics can be examined, or the characteristics of the long term mode induced, or the required stick force per speed error can be used to enable this gain to be calculated. None of the problems experienced with speed feedback at higher speeds were experienced. This is due to the fact that there are no right half plane zeros in the angle of attack to elevator transfer function, and therefore the angle of attack gain can be increased without fear of the left half plane poles close to the origin migrating into the right half plane.

In addition, no flare law is required due to the requirement to continually increase angle of attack in the flare, and therefore the K37 gain was set to zero. The gains for this control law may be found in appendix B.9.

4.6.11 Direct lateral law

This roll law has a simple wheel displacement to aileron gearing. In addition, there is a Q-pot which adjusts the control wheel force characteristics. However, the aircraft can be sluggish in roll with aileron alone, and therefore some spoiler gearing is used to increase the maximum achievable roll rate. However, the spoilers can excite the Dutch roll mode due to the yawing moment they produce, and therefore a yaw damper is also used.

This law was not used during the evaluations.

4.6.12 Fly-by-wire lateral law

The fly-by-wire lateral control law is typical for a fly-by-wire aircraft. It is based on the principle that zero spiral stability is desirable up to a specified angle of bank, in this case 35 degrees, so that the pilot does not have to work to maintain a specified turn rate. However, above 35 degrees, positive spiral stability is used since it prevents the pilot from achieving excessive angles of bank as he receives tactile feedback that the angle of bank is becoming excessively large.

The control gains for this law are gain scheduled with a q-pot to give a realistic feel system. The lateral laws used have been used previously, and are deemed to be appropriate for this aircraft and task.

4.6.13 Yaw Damper / Turn coordinator

The aircraft in question has quite a low Dutch roll damping ratio, and therefore the yaw damper / turn coordinator is a vital piece of equipment. It consists of the following feedbacks to the rudder.

1. Lateral acceleration. This provides the turn coordination function by minimising lateral acceleration during the turn.

2. Washed out yaw rate. This is used to increase the Dutch roll damping.

3. Washed out roll attitude. This is used to improve the lateral acceleration characteristics during turn entry and exit.

4.7 Control Law analysis against the criteria

The control law characteristics can be seen in the following set of tables 4.1 to 4.8 and in figures 4.6 to 4.9.

Bandwidth

The values for the pitch attitude and flight path bandwidths can be seen in table 4.1 and figures 4.6 and 4.7. It can be seen that all of the augmented configurations have level 1 bandwidth characteristics, but the augmented aircraft is borderline level 2 / 3.

Phase Delay

The phase delay characteristics can be seen on table 4.1 and figure 4.8. It can be seen that all of the configurations should not be PIO prone for the short term response characteristics.

Neal-Smith

The Neal-Smith characteristics can be seen in tables 4.2 to 4.4, and on figure 4.9 for the landing flight case. It can be seen that all of the resonance values are low, and all of the pilot compensation values are within level 1 limits except for the unaugmented aircraft, which requires excessive pilot compensation.

CAP and GCAP

Form table 4.5, it can be seen that all of the augmented control laws have approximately similar values of GCAP, although the CAP values do not correspond as well for some of the different control laws. This demonstrates why the Control Anticipation Parameter, in its current form, is not suitable for use with augmented, non-conventional response types, especially normal acceleration demand systems, since the results from different response types are not directly comparable.

It is also interesting to note that when actuator dynamics are included in the GCAP calculation, the results no longer are comparable with the CAP calculation. This is especially visible with the base law and law 1, which are angle of attack response types. Therefore when calculating the GCAP parameter, actuator dynamics must not be included in the calculation of the initial pitch acceleration, which is the parameter affected most by the actuator lag (compared to the final normal acceleration or first normal acceleration peak). This effect is also visible in the calculation of the steady manoeuvring force and pitch sensitivity criterion.

Short Term Mode Characteristics

From table 4.6, it can be seen that all of the short term mode damping ratios are approximately 0.7, but there is some variation in the short term mode natural frequencies to account for the requirement to design for a constant GCAP value.

Long Term Mode Characteristics

From table 4.7, it can be seen that the long term characteristics of the modes with static stability (whether through angle of attack or speed reference) are essentially of similar orders of magnitude. However, the damping ratios of the pitch rate laws are generally higher than those of the normal acceleration laws, and therefore the latter may require some additional form of long term mode damping.

Hoh's Proposed Flare Criterion

From table 4.8, it can be seen that the control laws which are either conventional or angle of attack meet the proposed 0.7 boundary for $\frac{d\gamma_{MAX}}{d\theta_{SS}}$ with the greatest margin. The laws with speed reference are also inside the boundary, but generally by a small margin, and finally the laws with a pitch attitude reference flare law are generally rated level 2 (i.e with $\frac{d\gamma_{MAX}}{d\theta_{SS}}$ values between 0.5 and 0.7. However, increasing the pitch attitude to stick force gain was found to increase the $\frac{d\gamma_{MAX}}{d\theta_{SS}}$ value for this type of flare law.

Law Number	ω_{BW_θ} (rad s^{-1})	$\omega_{BW_{\gamma P}}$ (rad s^{-1})	Phase rate (deg/Hz)	Phase Delay (s)	-180 deg phase Frequency (Hz)
Base	0.7836	0.4720	65.56	0.0910	0.3920
1	2.0402	1.0633	65.06	0.0900	0.7830
2	1.9843	0.9639	63.75	0.0890	0.7510
3	1.9761	0.8918	63.65	0.0880	0.7500
4	2.0637	1.0029	55.27	0.0770	0.8150
5	2.0595	1.0082	55.22	0.0770	0.8150
6	2.1211	0.8120	44.30	0.0620	0.9750
7	2.1328	0.8873	44.31	0.0620	0.9750
8	1.4023	0.6522	96.00	0.1330	0.5340
9	2.2854	1.2436	59.55	0.0830	0.8360
10	1.5585	0.8709	59.79	0.0830	0.7180

Table 4.1: Bandwidth and phase delays

	140 knots, flap 3, with actuator		140 knots, flap 3, no actuator	
	NS compensation (deg)	NS resonance	NS compensation (deg)	NS resonance
Base	81.00 lead	-3 dB	70.19 lead	-3 dB
1	15.24 lag	-2.95 dB	16.06 lag	-3 dB
2	9.087 lag	-3 dB	9.50 lag	-3 dB
3	8.723 lag	-3 dB	9.106 lag	-3 dB
4	13.71 lag	-2.993 dB	13.8 lag	-3 dB
5	13.55 lag	-3 dB	13.71 lag	-3 dB
6	3.617 lag	-2.314 dB	3.584 lag	-2.478 dB
7	3.887 lag	-2.26 dB	3.847 lag	-2.425 dB
8	13.56 lead	-2.992 dB	13.99 lead	-3 dB
9	26.65 lag	-3 dB	26.46 lag	-3 dB
10	12.97 lead	-3 dB	12.9 lead	-3 dB

Table 4.2: Neal-Smith compensation and resonance values for 140 knots flap 3

	140 knots, flap 4, with actuator		140 knots, flap 4, no actuator	
	NS compensation (deg)	NS resonance	NS compensation (deg)	NS resonance
Base	72.32 lead	-2.943 dB	62.91 lead	-3 dB
1	15.37 lag	-2.942	16.23 lag	-3 dB
2	10.43 lag	-2.994	10.9 lag	-3 dB
3	10.01 lag	-3 dB	10.49 lag	-3 dB
4	13.77 lag	-3 dB	14 lag	-3 dB
5	13.57 lag	-3 dB	13.82 lag	-3 dB
6	3.931 lag	-2.388 dB	3.955 lag	-2.545 dB
7	4.208 lag	-2.333 dB	4.226 lag	-2.491 dB
8	13.19 lead	-2.993 dB	13.44 lead	-3 dB
9	26.59 lag	-3 dB	26.55 lag	-3 dB
10	12.2 lead	-3 dB	11.88 lead	-3 dB

Table 4.3: Neal-Smith compensation and resonance values for 140 knots flap 4

	120 knots, flap 4, with actuator		120 knots, flap 4, no actuator	
	NS compensation (deg)	NS resonance	NS compensation (deg)	NS resonance
Base	114.4 lead	-2.996 dB	98.85 lead	-2.997 dB
1	7.818 lag	-2.341 dB	8.19 lag	-2.69 dB
2	4.163 lag	-2.48 dB	3.972 lag	-2.763 dB
3	3.27 lag	-2.612 dB	3.177 lag	-2.865 dB
4	7.1 lag	-2.388 dB	6.742 lag	-2.635 dB
5	6.653 lag	-2.466 dB	6.368 lag	-2.696 dB
6	4.791 lead	-2.575 dB	4.983 lead	-2.805 dB
7	4.158 lead	-2.468 dB	4.263 lead	-2.685 dB
8	29.58 lead	-3 dB	29.96 lead	-3 dB
9	18.6 lag	-2.476 dB	18.13 lag	-2.715 dB
10	4.62 lead	-.9274 dB	5.684 lead	-1.341 dB

Table 4.4: Neal-Smith compensation and resonance values for 120 knots flap 4

	140 knots, flap 3			140 knots, flap 4			120 knots, flap 4		
	no act CAP	no act GCAP	act GCAP	no act CAP	no act GCAP	act GCAP	no act CAP	no act GCAP	act GCAP
Base	0.188	0.190	0.099	0.210	0.208	0.107	0.188	0.187	0.096
1	0.714	0.672	0.366	0.728	0.668	0.364	0.741	0.689	0.371
2	0.713	0.550	0.303	0.733	0.566	0.311	0.760	0.593	0.323
3	0.711	0.563	0.310	0.733	0.578	0.317	0.756	0.609	0.330
4	0.720	0.626	0.368	0.745	0.626	0.368	0.750	0.641	0.369
5	0.719	0.632	0.372	0.744	0.632	0.371	0.749	0.649	0.373
6	0.190	0.569	0.364	0.197	0.569	0.364	0.195	0.619	0.391
7	0.191	0.565	0.362	0.198	0.567	0.363	0.197	0.616	0.389
8	0.682	0.295	0.160	0.731	0.294	0.160	0.736	0.286	0.153
9	0.943	0.860	0.511	0.973	0.859	0.510	0.951	0.843	0.488
10	0.339	0.378	0.216	0.360	0.376	0.216	0.520	0.464	0.261

Table 4.5: CAP and GCAP values with and without the elevator actuator (act)

	140 knots, flap 3		140 knots, flap 4		120 knots, flap 4	
	ω_{st} (rad s^{-1})	ζ_{st}	ω_{st} (rad s^{-1})	ζ_{lt}	ω_{st} (rad s^{-1})	ζ_{st}
Base	0.900	0.583	0.940	0.555	0.747	0.6083
1	1.750	0.703	1.749	0.702	1.483	0.7012
2	1.751	0.706	1.756	0.702	1.501	0.6939
3	1.748	0.707	1.755	0.703	1.498	0.6961
4	1.759	0.702	1.770	0.706	1.492	0.7003
5	1.758	0.703	1.770	0.706	1.491	0.7014
6	0.904	0.741	0.909	0.753	0.762	0.7434
7	0.906	0.740	0.911	0.751	0.764	0.7424
8	1.564	0.737	1.885	0.756	1.564	0.7368
9	2.014	0.621	2.023	0.625	1.680	0.6288
10	1.207	0.735	1.231	0.749	1.243	0.5772

Table 4.6: Longitudinal short term mode characteristics

	140 knots, flap 3			140 knots, flap 4			120 knots, flap 4		
	ζ_{lt}	ω_{lt} (rad s^{-1})	T_{lt} (s)	ζ_{lt}	ω_{lt} (rad s^{-1})	T_{lt} (s)	ζ_{lt}	ω_{lt} (rad s^{-1})	T_{lt} (s)
Base	0.025	0.150	42.00	0.092	0.140	44.88	0.050	0.151	41.53
1	0.072	0.152	41.39	0.126	0.148	42.51	0.097	0.172	36.53
3	0.208	0.143	44.00	0.269	0.144	43.57	0.319	0.155	40.64
5	0.165	0.126	49.83	0.230	0.127	49.67	0.244	0.139	45.30
7	0.059	0.112	56.00	0.129	0.112	56.10	0.087	0.112	56.05
8	0.094	0.136	46.27	0.145	0.136	46.30	0.127	0.154	40.67
9	0.177	0.101	62.27	0.263	0.101	62.09	0.259	0.111	56.20
10	0.054	0.137	45.80	0.108	0.137	45.90	0.071	0.163	38.62

Table 4.7: Longitudinal long term mode characteristics

	$\frac{d\gamma_{MAX}}{d\theta_{SS}}$	ω_{BW_θ} (rad s^{-1})	$\omega_{BW_{\gamma P}}$ (rad s^{-1})	$\omega_{BW_{\gamma CG}}$ (rad s^{-1})
Base	1.522	0.784	0.456	0.421
1	1.595	2.040	0.973	0.783
2	0.525	2.168	1.260	0.836
3	1.032	1.976	0.878	0.712
4	0.528	2.254	1.325	0.848
5	1.056	2.056	0.940	0.762
6	0.540	2.379	1.074	0.913
7	1.095	2.146	0.812	0.712
8	1.367	1.402	0.629	0.550
9	0.849	2.285	1.223	0.835
10	1.573	1.559	0.829	0.710

Table 4.8: Hoh's Flare Criterion Parameters, 120 knots, flap 4

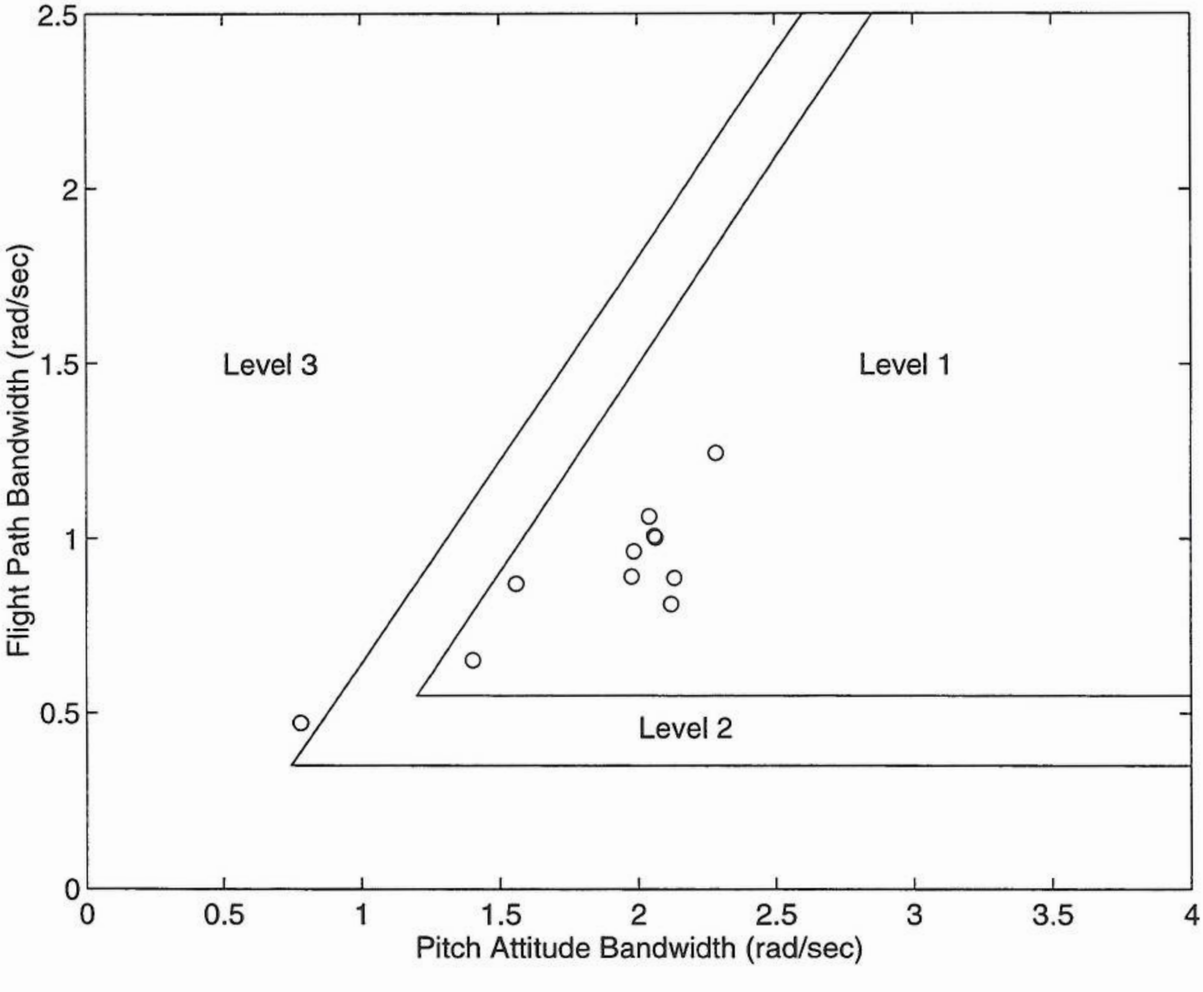

Figure 4.6: Pitch attitude bandwidth versus flight path bandwidth for the landing flight case (120 knots, flap 4)

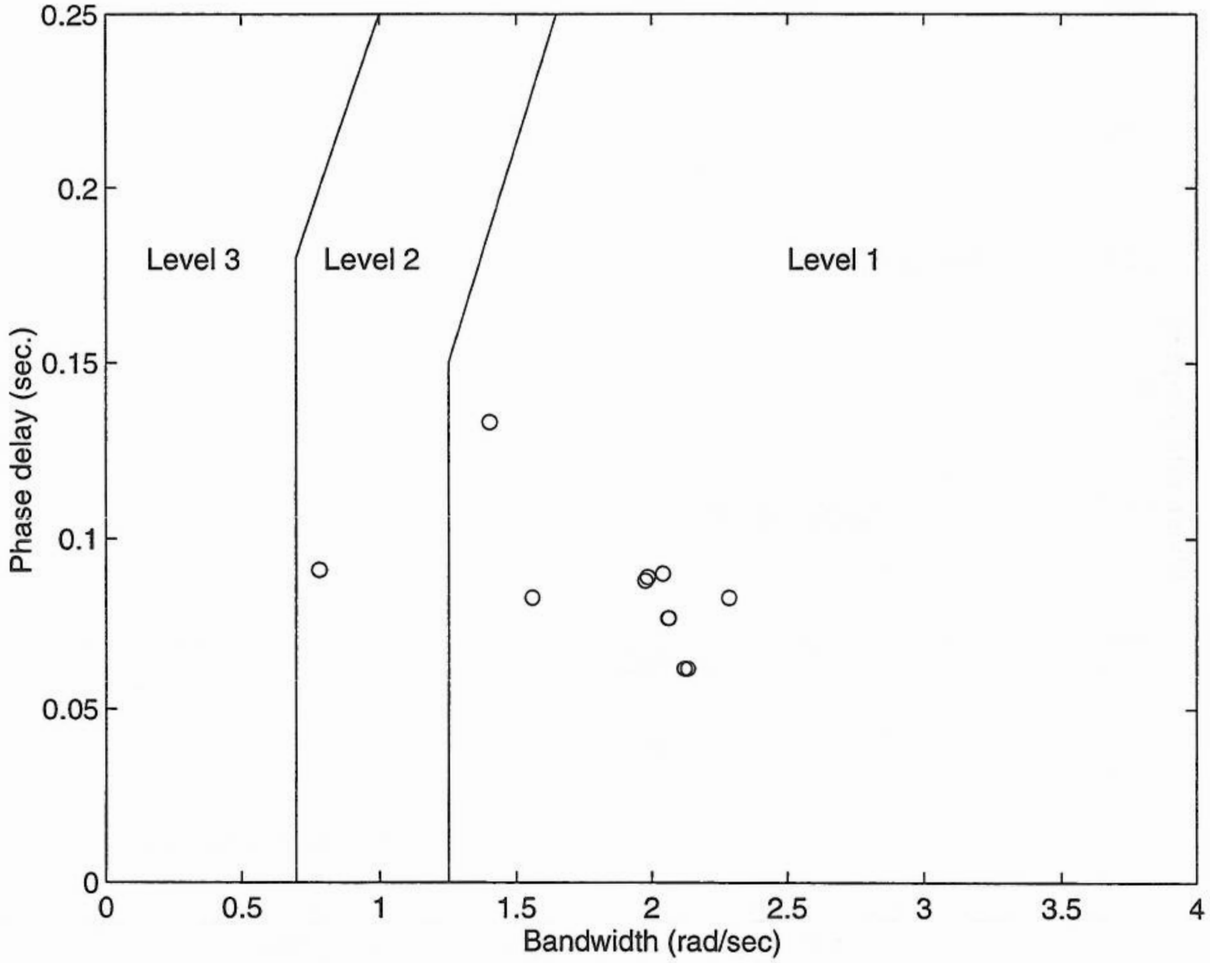

Figure 4.7: Pitch attitude bandwidth versus phase delay for the landing flight case (120 knots, flap 4)

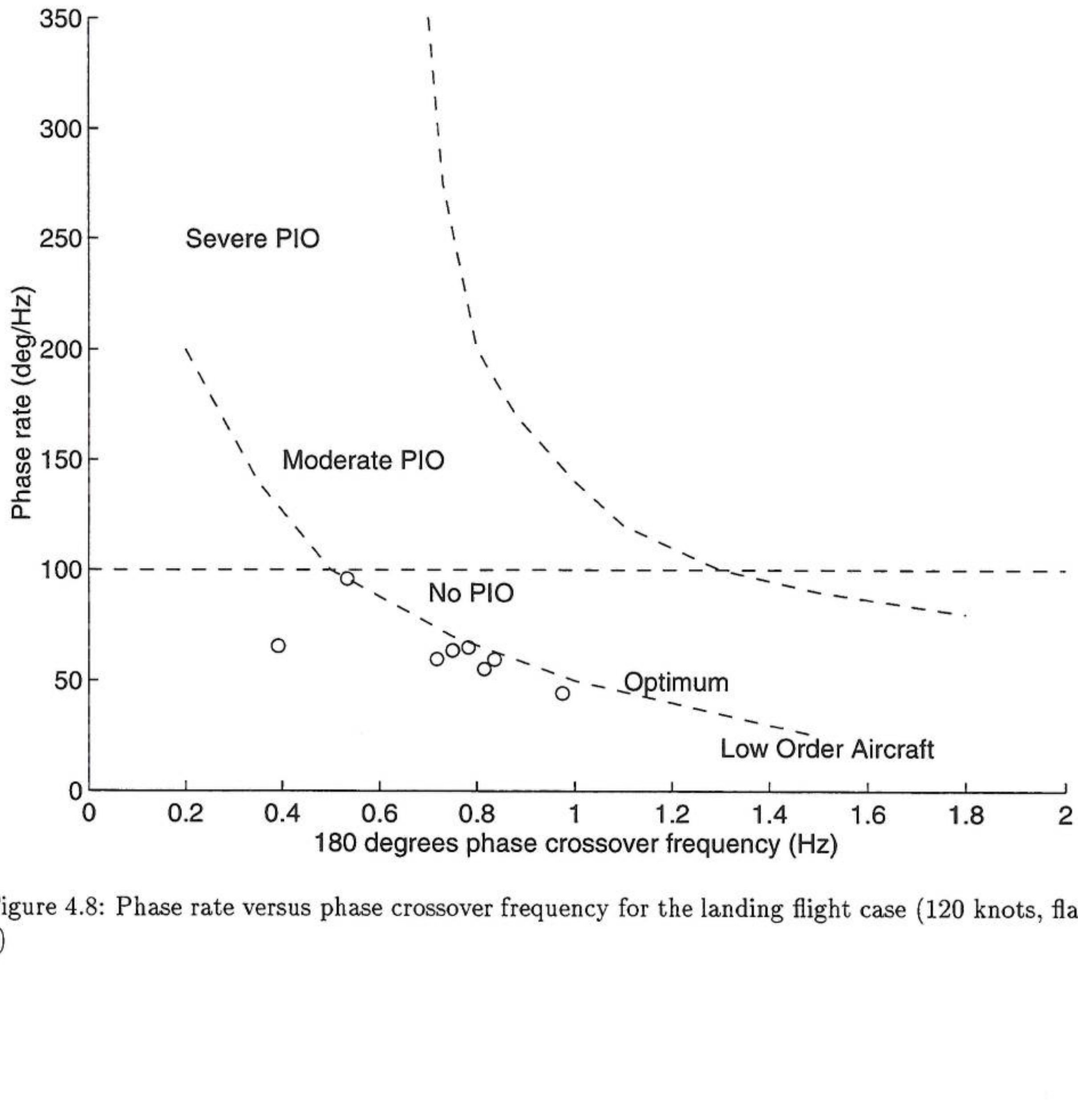

Figure 4.8: Phase rate versus phase crossover frequency for the landing flight case (120 knots, flap 4)

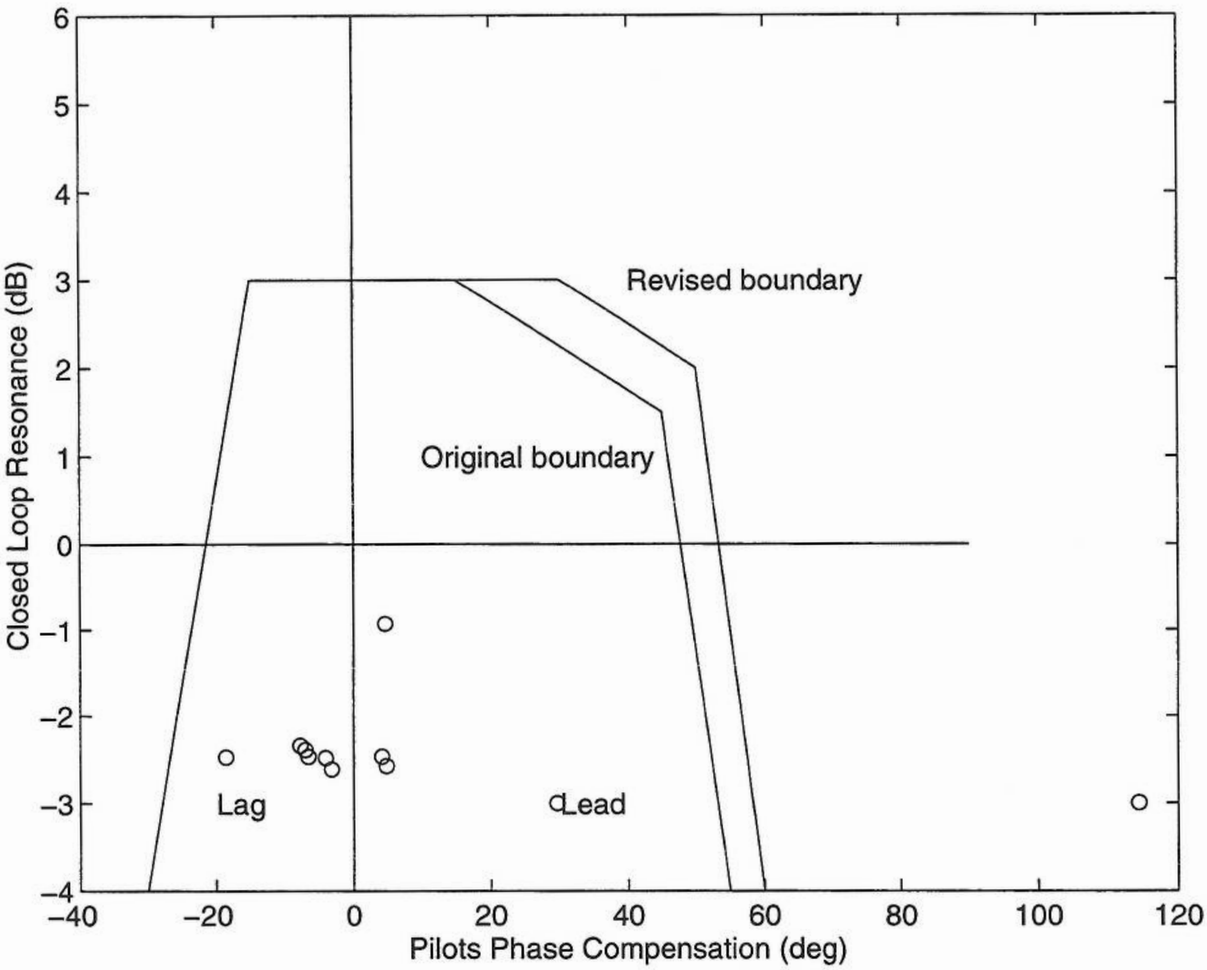

Figure 4.9: Neal-Smith Characteristics for the landing flight case (120 knots, flap 4)

Chapter 5

Flying Qualities Experiment Design

This chapter describes the evaluation procedure used for the handling qualities experiment. DeWitt [44] states that the tests must meet four definite criteria.

1. Instantaneously measurable performance
2. Operational relevance
3. Repeatability
4. Sufficient gain for the pilot to evaluate all axes.

Of these requirements, the last is the least important due to the primary investigation being restricted to the longitudinal axis, and therefore the desire to minimise disturbances in the lateral and directional axes.

These evaluations have been used to examine control law performance in the following areas.

1. Changes in airspeed
2. Flap deployment / reconfiguration
3. ILS tracking performance
4. The effects of an autothrottle
5. The effect of transitioning to the augmented aircraft.

The evaluation task used comprised the following segments, and the flare component can be seen in figure 5.1.

1. Start at 8 miles and 140 knots ($V_{REF} + \approx 20$ knots) configuration 3, and at 1500 feet on the QNH (1250 feet above aerodrome level). The aircraft was flown for 2 miles in this configuration to allow the evaluation pilot to stabilise the aircraft.

2. Flap deployment to landing configuration (configuration 4) at 6 miles. The flap lever was moved by the test administrator.

3. Intercept glideslope at approximately 4 miles.

4. When fully established on the glideslope, slow down to the final approach speed of 121 knots (V_{REF} + 5 knots).

5. Correct for any offset at 1 mile. A glideslope call was made by the GPWS, which was the cue for the pilot to make the correction into the touchdown zone.

6. Flare and land within the marked touchdown zone.

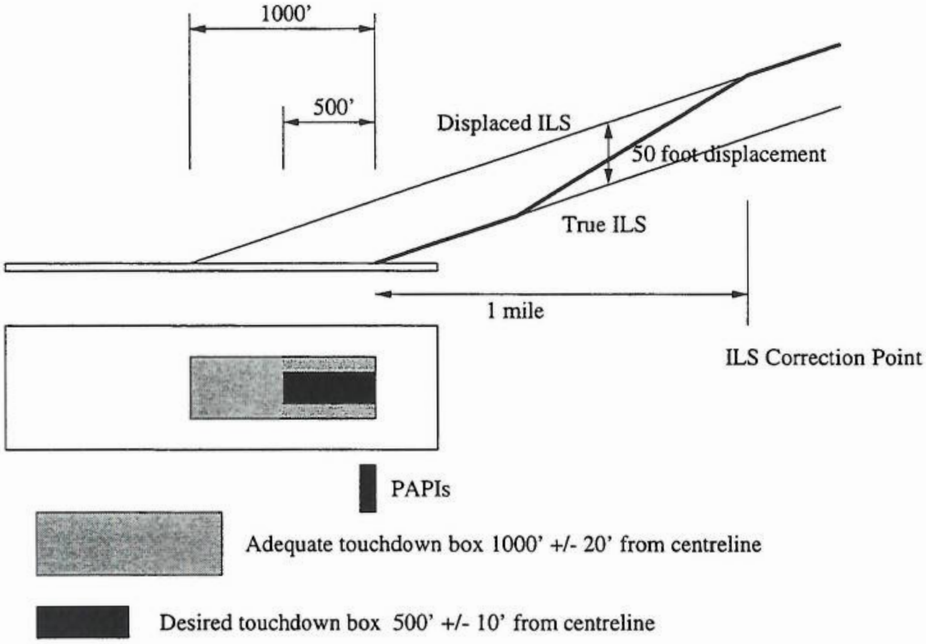

Figure 5.1: Evaluation procedure used

This evaluation segment was repeated a number of times. The evaluation pilot was initially given two or three of approaches with the unaugmented (baseline) aircraft to familiarise himself with the procedure. He then carried out either 2 or 3 approaches with the control law under consideration, but without the autothrottle active. After these approaches, the pilot and test administrator completed the first portion of the pilot comment card. The pilot then flew a further 1 or 2 approaches with the same control law and the autothrottle engaged, and then the pilot and test administrator completed the second portion of the pilot comment card. Finally, the pilot had an optional approach with the baseline aircraft before completing the final part of the comment card (which concerned the transition from the control law to the baseline in the case of failure).

Chapter 6

Handling Qualities Experiment Results

This chapter contains the results for each of the configurations flown during the evaluations. The results were recorded using the rating scales and comment cards which can be found in appendix D.

6.1 Evaluation Pilots

Four evaluation pilots took part in the evaluations. All are former RAF Test Pilots with previous handling qualities and large aircraft experience.

Pilot A - Roger Bailey.

After acquiring 5000 hours flying the C-130 Hercules for the RAF, he spent nearly 1000 hours as a flight instructor. After graduating from USAF TPS, he spent three years at RAE Bedford, nearly half as the squadron commander, primarily working on the Civil Avionics Programme, as well as working on Tornado and various Engineering Simulators. He took up his current position as the Chief Test Pilot at the Cranfield College of Aeronautics in 1990. Additionally, since 1990 he has flown the historic light aircraft of the Shuttleworth collection.

Pilot B - Mervyn Evans

After flying fast jets for the majority of his career in the Royal Air Force, he graduated from the US Navy TPS. He then served three years at RAE Farnborough, followed by three years as Principal Tutor, Fixed Wing at ETPS and two years as Principal Test Pilot at ITPS, Cranfield. He has considerable experience in fly-by-wire research and training, including involvement in the ETPS ASTRA Hawk and Calspan Learjet. He currently flies the Airbus A320 for Monarch Airlines.

Pilot C - Alan Foster.

After becoming a Qualified Flying Instructor in the RAF, he graduated from the ETPS at Boscombe Down. He then spent 6 years developing various fast jets. He left the RAF in 1985, and flew Boeing

Pilot	Configurations	Evaluations	Approaches
A	11	12	52
B	4	4	16
C	3	3	8
D	4	4	12
Total	11	23	88

Table 6.1: Evaluation Summary

727 for a couple of years with Dan Air before joining British Aerospace as a test pilot in 1988. Since then, he has assisted with the developed both the BAe 125 and BAe 146/Avro RJ series of aircraft, and he is currently a test pilot at Avro International Aerospace within BAe.

Pilot D - Dan Griffith.

After acquiring 2000 hours flying mainly fast jets in the RAF, he graduated from the USAF TPS. After this, he was the project pilot for the VAAC Harrier at the DRA Bedford Aerospace Research Squadron, and also flew the BAC 1-11, Canberra and HS 748, before briefly spending time as a Test Pilot at Boscombe Down. He now has over 4000 hours, and is a Test Pilot at the CAA Safety Regulation Group.

6.2 Evaluation Summary

In total, 4 pilots made 88 approaches during at total of 23 evaluations with 11 different control law configurations. Approximately half of these approaches were made with the use of an autothrottle. Pilot A had two evaluation sessions, while Pilots B, C and D had a single evaluation session each. Table 6.1 gives a summary of these results.

The evaluations were performed on the following dates

Session Number	Date
A-1	9th September 1996.
B-1	12th September 1996.
C-1	1st October 1996.
D-1	3rd October 1996.
A-2	9th October 1996.

In addition, a calibration session was carried out by the author in July 1996 to check the simulator performance, and that the control laws were performing as designed. Minor modifications were made after that session, mainly to some of the control gains and to the implementation of the

Law	Pilot A	Pilot B	Pilot C	Pilot D	Median
0	4	3	4	4	4
1	3				
2	4	4			4
3	2			3	2.5
4	3				
5	3	3	3		3
6	2,2	3	1	1.5	2
7	2				
8	4				
9	2			4	3
10	4				

Table 6.2: Reconfiguration Cooper Harper Ratings without Autothrottle

speed reference for the speed stable control laws. No problems were experienced with simulator performance during the evaluations, although the lack of visual and motion cues resulted in many of the landings being excessively firm.

6.3 Cooper Harper Rating Charts.

The Cooper Harper ratings for the reconfiguration, approach, flare and an overall rating can be found in tables 6.2 to 6.9. The data is also plotted on figures C.7 to C.14.

Law	Pilot A	Pilot B	Pilot C	Pilot D	Median
0	3	4	4	4	4
1	2				
2	2	4			3
3	1			2.5	1.75
4	2	3	3		3
5		3			
6	2,1	4	1	1.5	1.5
7	1				
8	3				
9	2			4	3
10	3				

Table 6.3: Reconfiguration Cooper Harper Ratings with Autothrottle

Law	Pilot A	Pilot B	Pilot C	Pilot D	Median
0	3	4	3	4	3.5
1	3				
2	4	2			3
3	2			3	2.5
4	3				
5	2	3	3		3
6	2,2	2	2	2.5	2
7	3				
8	4				
9	3			4	3.5
10	4				

Table 6.4: Approach Cooper Harper Ratings without Autothrottle

Law	Pilot A	Pilot B	Pilot C	Pilot D	Median
0	2	4	4	4.5	4
1	2				
2	4	2			3
3	2			2	2
4	2				
5	2	2	3		2
6	2,2	4	2	1.5	2
7	2				
8	4				
9	4			3	3.5
10	3				

Table 6.5: Approach Cooper Harper Ratings with Autothrottle

Law	Pilot A	Pilot B	Pilot C	Pilot D	Median
0	3	2	2	3	2.5
1	2				
2	3	2			2.5
3	3			2	2.5
4	3				
5	2	2	4		2
6	3,3	2	2	2	2
7	2				
8	6				
9	2			3	2.5
10	2				

Table 6.6: Flare Cooper Harper Ratings without Autothrottle

Law	Pilot A	Pilot B	Pilot C	Pilot D	Median
0	3	4	2	4	3.5
1	2				
2	5	2			3.5
3	3			2	2.5
4	3				
5	2	2	4		2
6	4,2	2	2	1.5	2
7	2				
8	6				
9	4			2	3
10	2				

Table 6.7: Flare Cooper Harper Ratings with Autothrottle

Law	Pilot A	Pilot B	Pilot C	Pilot D	Median
0	3	4	3	4	3.5
1	3				
2	4	2			3
3	3			3	3
4	3				
5	2	3	3		3
6	2,3	3	2	2.5	2.5
7	3				
8	5				
9	3			4	3.5
10	3				

Table 6.8: Overall Cooper Harper Ratings without Autothrottle

Law	Pilot A	Pilot B	Pilot C	Pilot D	Median
0	2.5	4	3	4	3.5
1	2				
2	3	2			2.5
3	2			2.5	2.25
4	2				
5	2	2	3		2
6	3,2	4	2	1.5	2
7	2				
8	5				
9	3			3	3
10	3				

Table 6.9: Overall Cooper Harper Ratings with Autothrottle

6.4 Touchdown Performance

The touchdown performance data can be found in table 6.10 and 6.12. The data can also be found on figures C.1 to C.6.

Code	Meaning
Eval	Evaluation Number (unique to this law / pilot).
Type	Approach type.
famil	Familiarisation approach.
1 app	1st manual throttle approach.
1 athr	1st autothrottle approach.
base	Baseline.
V_{50}	Airspeed at 50 feet (knots).
V_{td}	Airspeed at touchdown (knots).
$\dot{H}_{50}$	Sink rate at 50 feet (feet per second).
$\dot{H}_{td}$	Sink rate at touchdown (feet per second).
X_{td}	X position on runway at touchdown (feet).
Y_{td}	Y position on runway at touchdown (feet).

Pilot	Law	Eval	Type	V_{50}	$\dot{H}_{50}$	V_{td}	$\dot{H}_{td}$	X_{td}	Y_{td}
A	0	1	2 app	118.0	10.1	113.2	7.3	95.5	-5.2
A	0	1	1 athr	121.1	12.2	118.5	3.8	-105.4	6.3
A	0	1	2 athr	121.2	10.2	118.9	4.6	56.0	1.0
A	6	2	famil	118.2	9.4	112.0	4.3	55.3	3.1
A	6	2	1 app	118.3	9.7	112.0	5.3	223.0	0.3
A	6	2	1 athr	121.1	13.1	113.9	2.2	79.6	7.7
A	0	2	base	116.7	10.1	111.7	7.5	-76.5	-4.1
A	9	3	famil	120.1	11.2	113.2	4.5	220.7	-1.9
A	9	3	1 app	120.0	9.0	114.7	3.3	39.2	7.9
A	9	3	1 athr	121.1	11.0	117.0	6.1	113.9	-3.4
A	9	3	1 athr	120.9	7.5	116.2	7.5	-0.9	3.8
A	0	3	base	119.1	10.2	116.0	4.3	-143.1	11.7
A	3	4	famil	118.5	12.3	113.5	4.9	-42.9	-0.7
A	3	4	1 app	120.0	11.2	113.3	4.3	125.7	3.2
A	3	4	1 athr	121.3	14.6	114.1	1.5	219.9	0.2
A	3	4	2 athr	121.2	12.5	115.3	3.1	-128.2	-0.6
A	0	4	base	120.5	10.1	115.4	3.0	-19.6	-1.2
A	1	5	famil	118.8	8.1	113.7	6.1	88.1	3.9
A	1	5	1 app	117.5	8.4	112.2	5.8	194.5	3.5
A	1	5	1 athr	121.2	10.6	114.7	3.6	-22.5	1.4
A	6	6	famil	118.3	7.2	110.9	6.4	283.3	-0.4
A	6	6	1 app	119.8	9.8	113.8	4.5	-299.1	5.8
A	6	6	1 athr	121.0	9.8	115.6	3.1	20.0	0.9
A	7	7	famil	119.7	11.0	111.1	5.2	236.5	2.9
A	7	7	1 app	120.9	11.0	116.2	3.1	172.8	2.8
A	7	7	1 athr	121.0	10.3	115.8	4.6	54.0	4.8
A	0	7	base	119.0	14.1	114.5	4.4	-4.9	2.8
A	0	19	prac	117.7	11.0	115.4	6.7	-256.0	-3.6
A	0	19	prac	118.5	10.5	112.1	3.2	62.0	9.0
A	10	19	famil	119.5	9.3	113.3	4.0	216.0	-3.3
A	10	19	1 app	122.1	9.0	114.8	1.6	290.0	5.3
A	10	19	2 app	120.9	11.1	112.2	1.0	214.0	9.2
A	10	19	3 app	120.5	8.6	113.3	3.6	235.0	-7.5
A	10	19	1 athr	120.9	9.1	116.3	5.4	217.0	8.2
A	10	19	2 athr	121.0	9.4	116.5	5.1	-158.0	-3.3
A	10	19	3 athr	121.1	12.0	112.6	1.4	242.0	5.5
A	5	20	famil	118.9	9.7	110.1	2.3	97.0	9.8
A	5	20	1 app	120.9	8.7	113.0	3.6	173.0	11.6
A	5	20	1 athr	121.3	10.5	114.2	4.6	-7.0	6.0

Table 6.10: Touchdown performance data (1).

Pilot	Law	Eval	Type	V_{50}	$\dot{H}_{50}$	V_{td}	$\dot{H}_{td}$	X_{td}	Y_{td}
A	2	21	famil	120.0	9.5	112.4	4.8	12.0	-0.5
A	2	21	1 app	119.6	7.8	113.6	4.0	9.0	11.1
A	2	21	1 athr	121.4	9.9	112.9	5.9	121.0	2.1
A	2	21	2 athr	120.9	11.0	101.1	3.3	957.0	5.3
A	2	21	3 athr	121.0	10.8	113.3	3.8	-174.0	0.4
A	8	22	famil	121.4	9.9	106.8	3.4	528.0	8.7
A	8	22	1 app	121.0	5.9	107.6	1.5	544.0	0.4
A	8	22	1 athr	120.9	8.3	112.3	3.3	230.0	-3.3
A	8	22	2 athr	120.8	9.4	103.2	6.6	859.0	-9.5
A	4	23	famil	120.5	9.4	113.8	3.4	-102.0	3.9
A	4	23	1 app	120.8	8.9	113.7	3.1	-31.0	7.1
A	4	23	1 athr	121.1	11.4	103.4	2.8	834.0	7.4
A	4	23	2 athr	120.9	9.1	113.3	2.9	61.0	-4.1
B	0	8	famil	125.0	12.4	118.5	6.4	50.2	0.2
B	0	8	1app	119.8	9.1	116.5	7.1	-12.5	4.9
B	0	8	2app	121.3	11.4	116.9	6.0	-86.5	1.8
B	0	8	1athr	121.1	11.9	119.0	9.7	-145.5	-2.6
B	0	8	2athr	121.1	13.2	117.0	5.2	-82.8	1.0
B	6	9	famil	120.9	10.1	114.9	4.3	107.8	1.0
B	6	9	app1	120.5	7.4	115.8	6.7	73.7	-1.7
B	6	9	athr1	120.9	7.7	115.3	5.5	-41.1	-1.0
B	6	9	athr2	120.8	7.9	114.8	4.4	-5.1	6.6
B	2	10	famil	122.7	9.6	116.4	3.8	324.8	6.8
B	2	10	1app	121.1	10.9	116.1	3.4	120.0	3.8
B	2	10	1athr	120.7	8.4	116.6	6.0	-56.8	6.1
B	2	10	2athr	120.8	7.4	120.0	4.4	40.9	14.8
B	5	11	famil	122.5	13.6	118.2	5.7	123.3	10.9
B	5	11	1app	120.5	9.8	114.7	4.7	2.1	-0.2
B	5	11	1athr	120.7	7.4	116.2	7.4	5.2	5.6
C	0	12	famil	120.0	13.6	115.2	5.9	-216.0	-3.8
C	0	12	1 app	121.7	15.5	117.4	7.2	-195.0	3.2
C	0	12	1 athr	121.2	12.6	117.8	7.9	-183.0	3.5
C	6	13	1 app	111.3	10.4	106.8	5.4	-272.0	1.6
C	6	13	1 athr	120.0	11.3	117.0	9.6	-204.0	0.7
C	5	14	famil	117.5	13.9	114.0	9.1	-245.0	-0.7
C	5	14	1 app	115.7	10.6	109.3	7.0	-273.0	4.2
C	5	14	1 athr	120.6	14.6	116.2	6.2	-226.0	0.0

Table 6.11: Touchdown performance data (2).

Pilot	Law	Eval	Type	V_{50}	$\dot{H}_{50}$	V_{td}	$\dot{H}_{td}$	X_{td}	Y_{td}
D	0	15	famil	126.8	15.9	123.7	8.3	145.0	0.1
D	0	15	1 app	121.2	11.8	119.2	8.5	47.0	-0.7
D	0	15	2 app	124.0	13.1	120.8	8.8	101.0	1.8
D	0	15	1 athr	121.9	19.9	119.0	8.2	68.0	3.5
D	3	16	famil	122.9	15.8	120.4	9.2	201.0	5.3
D	3	16	1 app	121.2	13.5	117.9	7.8	139.0	2.8
D	3	16	1 athr	121.3	10.4	118.3	8.6	91.0	1.9
D	6	17	famil	126.9	16.3	123.6	7.0	83.0	-2.1
D	6	17	1 app	124.8	11.8	121.1	9.6	169.0	-7.4
D	6	17	1 athr	121.6	13.9	117.4	6.1	-97.0	1.9
D	9	18	1 app	124.1	13.5	120.3	6.3	149.0	2.6
D	9	18	1 athr	121.3	13.8	117.0	7.1	-16.0	0.9

Table 6.12: Touchdown performance data (3).

6.5 Bedford Workload Ratings

The Bedford Workload ratings for the reconfiguration and approach for both non-autothrottle and autothrottle configurations can be found in tables 6.13 to 6.16. The data is also plotted on figures C.15 to C.18.

6.6 PIO Ratings

The overall PIO ratings for both non-autothrottle and autothrottle configurations can be found in tables 6.17 and 6.18. The data is also plotted on figures C.19 and C.20.

6.7 NASA TLX Ratings

The TLX ratings for the approach for both non-autothrottle and autothrottle cases can be found in tables 6.19 and 6.20.

Some analysis was done on the TLX ratings, but there was a large spread in the results, and since there were insufficient results to perform a statistical analysis with a high degree of certainty, the analysis was carried no further.

The problem with TLX is the necessity for a pilot to give a rating without having any prompts as to the procedure that he must follow in order to award a given rating. For a small number of pilots therefore, the results do not give an overall reflection on the workload, although they do give a reasonable indication of the source of the workload. For these evaluations, it is sufficient to say

Law	Pilot A	Pilot B	Pilot C	Pilot D	Median
0	3	3	3	3	3
1	3				
2	4	4			4
3	1			2.5	1.75
4	3				
5	3	3	3		3
6	2,2	3	1	1	2
7	2				
8	4				
9	2			4	3
10	4				

Table 6.13: Reconfiguration Bedford Ratings without Autothrottle

Law	Pilot A	Pilot B	Pilot C	Pilot D	Median
0	3	4	3	3	3
1	3				
2	4	2			3
3	2			2.5	2.25
4	3				
5	2	3	3		3
6	2,3	2	2	2	2
7	3				
8	4				
9	3			4	3.5
10	4				

Table 6.14: Reconfiguration Bedford Ratings with Autothrottle

Law	Pilot A	Pilot B	Pilot C	Pilot D	Median
0	2	4	4	2.5	3.25
1	2				
2	2	4			3
3	1			2.5	1.75
4	2				
5	2	3	3		3
6	1,1	3	1	1	1
7	1				
8	3				
9	2			3	2.5
10	3				

Table 6.15: Approach Bedford Ratings without Autothrottle

Law	Pilot A	Pilot B	Pilot C	Pilot D	Median
0	2	4	4	3	3.5
1	2				
2	4	2			3
3	2			2	2
4	2				
5	2	2	2		2
6	1,2	2	2	1	2
7	2				
8	3				
9	3			3	3
10	3				

Table 6.16: Approach Bedford Ratings with Autothrottle

Law	Pilot A	Pilot B	Pilot C	Pilot D	Median
0	1	1	1	3	1
1	1				
2	1	1			1
3	1			2	1.5
4	1				
5	1	1	2		1
6	1,1	2	1	2	1
7	1				
8	1				
9	1			2	1.5
10	1				

Table 6.17: PIO Ratings without Autothrottle

Law	Pilot A	Pilot B	Pilot C	Pilot D	Median
0	1	2	2.5	4	2.25
1	1				
2	1	1			1
3	1			2	1.5
4	1				
5	1	1	1		1
6	1,1	1	1	2	1
7	1				
8	1				
9	1			2	1.5
10	1				

Table 6.18: PIO Ratings with Autothrottle

Law	Pilot	BED	TLX	MD	PD	TD	P	E	F
0	A1	3	57.00	240	0	100	275	180	60
0	B	3	56.67	280	60	20	250	140	100
0	C	3	53.00	375	20	50	200	150	0
1	A1	3	46.00	160	0	70	350	90	20
2	B	4	17.33	60	15	25	100	30	30
2	A2	4	52.67	350	0	120	60	220	40
3	A1	1	43.33	140	0	70	300	120	20
4	A2	3	51.00	350	0	90	60	220	45
5	B	3	46.00	180	60	30	250	100	70
5	C	3	60.00	450	30	40	200	180	0
5	A2	3	46.33	325	0	90	50	200	30
6	A1	2	38.33	180	0	90	175	105	25
6	A1	2	38.33	120	0	60	300	75	20
6	B	3	21.00	80	30	25	100	40	40
6	C	1	36.33	250	5	40	160	90	0
7	A1	2	38.67	100	0	50	300	105	25
8	A2	4	57.33	350	0	120	80	260	50
9	A1	3	43.67	160	0	50	300	120	25
10	A2	4	52.00	325	0	90	80	240	45

Table 6.19: NASA TLX Ratings and Components without Autothrottle

that the source of the workload was mental demand, plus the demand induced on the pilot by the required performance.

The codes in the TLX tables have the following meanings :

Code	Meaning
BED	Bedford Workload Rating for the approach.
TLX	Overall NASA TLX Score for the approach.
MD	Mental Demand.
PD	Physical Demand.
TD	Temporal Demand.
P	Performance.
E	Effort.
F	Frustration.

Law	Pilot	BED	TLX	MD	PD	TD	P	E	F
0	A1	2	35.67	140	0	70	225	75	25
0	B	4	66.00	320	70	50	250	160	140
0	C	4	61.33	400	10	100	200	210	0
1	A1	2	37.00	160	0	50	275	60	10
2	B	4	15.67	60	15	15	75	30	40
2	A2	2	46.33	325	0	90	60	180	40
3	A1	2	27.00	80	0	40	200	75	10
4	A2	2	45.67	350	0	75	40	180	40
5	B	2	43.00	180	60	25	200	100	80
5	C	2	48.33	300	10	50	200	165	0
5	A2	2	41.33	325	0	75	40	160	20
6	A1	1	38.33	180	0	40	225	105	25
6	A1	2	36.67	120	0	50	300	60	20
6	B	2	25.33	120	25	35	100	40	60
6	C	2	30.67	200	10	50	140	60	0
7	A1	2	28.33	60	0	40	250	60	15
8	A2	3	50.00	325	0	105	60	220	40
9	A1	3	48.67	140	0	60	350	135	45
10	A2	3	38.00	225	0	90	60	160	35

Table 6.20: NASA TLX Ratings and Components with Autothrottle

6.8 Control Law Summaries

This section summarises the flying qualities of each of the configurations flown, i.e. the baseline aircraft plus 10 control laws. The pilot comment cards, from which these comments were derived can be seen in Appendix E.

Lateral / directional effects were not a factor in any of the evaluations.

6.8.1 Specific Comments

Basic Aircraft

The basic aircraft was flown by all of the pilots and used as a baseline reference against all of the other configurations were compared. The pilots were informed that this is how the aircraft would handle upon failure of the primary flight control system, and therefore this configuration was also used as the reference for the failure part of the handling qualities evaluations.

During reconfiguration, this aircraft generally had low forces with desirable trimming characteristics. This aircraft had a mixture of CHR 3 and 4 from each of the pilots, and all of them perceived a heave in the flight path response.

During the approach, the pilots comments confirmed that the aircraft had acceptable forces and trim characteristics. However, the aircraft is not solid in attitude, and the airspeed control was one of the more difficult features of this configuration. This could have been due to a number of factors, one pilot commented on the excessive throttle to thrust gearing, and comments were received concerning the displays, specifically the airspeed tape. Overall, the CHRs were a mixture of 3 and 4.

The flare was rated better than the approach, with CHRs of 2 and 3. The forces were appropriate, and it was generally possible to control the flare parameters.

With autothrottle, the CHRs were generally degraded by about 1 point. This is due to the large pitching moment that occurs with power inputs, and the active autothrottle, which generally holds speed well, but is continually commanding power changes. The pilots found this disturbing during the approach due to the seemingly uncommanded pitching motions arising from the autothrottle.

Bedford workload ratings were generally 3 to 4 for this configuration, and no great change was noted for the autothrottle. This configuration was not deemed to be PIO prone in short term, but there was a long term PIO due to the autothrottle effects.

Generally, this configuration flew like a conventional aircraft, but lacked strong attitude stability, and the autothrottle caused quite a severe pitching moment which was detrimental to the task.

Augmented Angle of Attack

This configuration was flown by one pilot, and generally received CHRs which were one point better than the baseline aircraft. The response characteristics during the reconfiguration were better than the baseline, making the task easier. The trim characteristics were desirable, and the speed control was similar to the baseline. The pilot thought that this configuration had a slightly greater tendency to float compared to the baseline. This configuration received almost identical Bedford ratings to the baseline aircraft.

The pilot commented that under the failure case, the pilot could not just be expected to cope, and would require some approaches at each base check. He commented that the most difficult part of the transition would be the flare, and the pilot may have a slightly increased workload in the case of loss of autothrottle.

Generally, this configuration flew like a conventional aircraft, and was an improvement over the baseline aircraft, with no real problems likely to be experienced in making the transition under the failure case to the unaugmented aircraft

Pitch rate

This configuration was evaluated by two pilots. It was found to be conventional during the reconfiguration task, with a slight balloon up, giving CHRs of 4 due to the requirement to correct for the balloon. This configuration was perhaps a little more responsive than previous configurations, but this did not seem to reduce the ratings. One pilot rated CHR 2 for the approach, and seemed to like the improved attitude solidness and he found no problems with pitch attitude / flight path consonance (or relationship). The second pilot commented on the attitude stability, but gave the configuration a CHR 4 due to the lack of trimming.

This configuration is attitude command in the flare. The control forces were characterised as low but positive, and there was a need to hold a force in the flare. The flare itself was conventional and received CHR 2 and 3.

The autothrottle had a marked effect on workload reduction during the evaluation segment. However, there was a tendency for the aircraft to drop down below the glideslope as the speed reduced. This is due to the nature of the control law. When the autothrottle is engaged, the speed reduced quite quickly, and therefore the pilots need to steadily increase the angle of attack through increasing the pitch attitude in order to maintain lift, and therefore the glideslope. If this did not happen then the aircraft would drop below the glideslope. In practice, a conventional autothrottle would not slow the aircraft down as quickly as the one designed for this aircraft, and the required increase in pitch attitude would be more gradual. The autothrottle had little effect on the CHR or Bedford workload rating, and this configuration was not deemed to be PIO prone.

The transition from this control law to the unaugmented aircraft would probably be more difficult than the previous laws due to the lack of trimming with this law. This is quite a major change in philosophy, and therefore regular training would be required to enable the failure case to be coped with.

Generally, this configuration flew well, and the pilots liked the solid attitude dynamics. However, there were flight path control problems on the approach due to the nature of the law, and it was unconventional due to the lack of trimming, which would make transitioning to the basic aircraft in the failure case more difficult.

Pitch rate with speed stability

This configuration was evaluated by two pilots. For the reconfiguration, it required a nose down pitching motion, which is conventional. The forces were light and appropriate, and there was no requirement to trim. It received CHRs of 2 and 3 for the reconfiguration. In the approach, it seemed to behave like a conventional trimming aircraft, with the response dynamics and feel system being about right. The second pilot flew it using a backside technique, where the airspeed was controlled with the stick, and the descent rate controlled with the throttles, although he commented that a conventional technique could be used.

For the approach, the trim to speed nature of the law, combined with the trim speed bug made the pilot very speed aware. In addition, it also gave this law a conventional feel, with much more attitude stability.

The flare was deemed to be slightly less light than some of the other corrections, resulting in a slight tendency to underflare. However, the pilot who made these comments tended to like lighter forces in the flare compared to the other pilots, and he also made the comment that he did not need to be careful.

The autothrottle also had a marked effect on workload reduction. This configuration was rated CHR 2 for the autothrottle approach. The same flight path effect was found as with the pure pitch rate command system.

The transition from this control law to the unaugmented aircraft would be easier than the pure pitch rate law due to the trimming requirement for this law. The pilot would probably find the unaugmented aircraft quite difficult due to the lack of pitch stability, but the transition would certainly be possible.

Pitch rate with angle of attack stability

This law was evaluated by one pilot. He found that the trim rate was generally too slow, resulting in reduced ratings. Since this law had angle of attack stability, there was a requirement to trim for both flap and airspeed changes. He also found that it was a little too responsive, which led to over-controlling tendencies in the offset correction. No problems were experienced when the law was on trim.

The responsiveness results in the landing attitude being achieved a little too early, resulting in a floating tendency. Again, the autothrottle reduces the workload, but the problems with over-responsiveness and low trim rate still exist. It was this pilot's opinion that there would be no problem in making the transition to the baseline aircraft.

In general, this configuration had acceptable dynamics, but there were problems with the low trim rate and also the slightly high responsiveness.

C*

The C* control law was evaluated by one pilot. He found the force for the reconfiguration pretty light, with conventional response characteristics and a CHR of 3. The approach also received a CHR of 3, with appropriate forces and a quick, but not abrupt response. The airspeed control was satisfactory, and the pitch attitude / flight path consonance was quite good. The flare also received a CHR of 3, with a flare which was very similar to being conventional. Again, this pilot did not like the lack of trimming.

Introducing the autothrottle reduced the workload, resulting in CHRs of 2 for both the reconfiguration and approach. The Bedford workload rating also improved for both of these tasks from 3 to 2. No PIO tendencies were noticed.

As with the pure pitch rate law, problems would be experienced in transitioning to the unaugmented aircraft in the failure case because the pilot would not be used to having to trim due to the lack of trimming, and loss in attitude stability.

In general, this was a non-trimming rate demand system with acceptable dynamics.

C* with speed stability

This control law was evaluated by three pilots. For the reconfiguration task, the response was conventional, and there was no requirement to trim, although the aircraft still ballooned up, and therefore there was the requirement to trim. It received a CHR of 3 from every pilot who evaluated it.

For the approach, two of the pilots found the dynamics acceptable, with a solid feel in attitude, and no problems with speed control. There was also a requirement to trim to speed, which was conventional, although one pilot commented that there was not sufficient stick force with a given speed error to be of great assistance. However the third pilot found that this control law was 'confusing' and did not seem to fit into any defined category. This may have been due to the trim to speed system, which the pilot was not familiar with. Even so, it received CHRs of 2 and 3 for the approach.

In the flare, the control forces were fairly light, and it was deemed to respond well by two of the pilots, receiving a CHR of 2 from them. The third pilot found that he had to reassess the flare and make a second correction, and therefore awarded a CHR of 4.

The autothottle was again found to reduce the workload for the task, and as with the pitch rate with speed trim law, the pilot would have similar problems in making the transition to the baseline aircraft, such as the lower attitude stability, and the lack of autothrottle.

In summary, this law had similar properties to the pitch rate law with speed stability, and has handling qualities close to an improved basic aircraft.

C* with angle of attack stability

As with the pitch rate with angle of attack stability, problems were experienced with the low trim rate for this configuration. Two pilots evaluated this configuration, and the comments were similar to those for the pitch rate with angle of attack trim law. These comments are reflected in the CHRs for the laws.

Normal acceleration

This control law was evaluated on five separate occasions by all four pilots and received the best overall ratings. For the reconfiguration task, it held the flight path, and therefore the only required pilot correction was an increase in thrust to offset the drag rise.

During the approach, the configuration held the current fight path, even as the airspeed changed, and therefore the required compensation as the airspeed decreased was negligible. This resulted in a very low workload and correspondingly low CHR. The stick forces and response characteristics were deemed appropriate, and the pitch attitude to flight path consonance was suitable.

The flare was mechanised using a pitch attitude demand law, and this gave the same characteristics as with previous pitch attitude flare laws. One evaluation pilot noticed a possible PIO problem in the flare, but later decided that it wasn't actually there.

The autothrottle provided for a very low workload configuration, and resulted in the pilots being able to sit back and let the aircraft fly itself. This was noticed by several pilots. These configurations (normal acceleration plus autothrottle) were the best rated of the whole evaluations, and received lowest workload ratings. However, some of the pilots were prone to letting the errors build up since they knew that they could easily correct them. Also, there was a tendency for the aircraft to pitch up by itself as it slowed down along the glideslope due to the angle of attack increasing to maintain lift, and one pilot did not like this as he perceived it as an uncommanded pitch-up.

The comments concerning the handling qualities under failure indicate that this control law has handling qualities which are significantly different to the baseline aircraft. The requirement to trim and the significantly different response nature of this response type would result in the pilot operating with this law as the primary law experiencing the most problems in the failure case.

In general, this law is a very low workload law, but is non-conventional, and can result in the pilot sitting out of the loop. In addition, it has quite different characteristics to the unaugmented aircraft.

Normal acceleration with speed stability

This law was flown by one pilot. He found that it had characteristics very similar to the basic normal acceleration law, but the requirement to trim for speed changes was favourable. However he commented that this law was not as nice to fly as the C*U or qU laws.

The control forces were very low during the reconfiguration, again with no requirement to trim. During the approach, the control forces and response characteristics seemed appropriate, with no problems experienced with either the aircraft slowing down or maintaining the glideslope. The flare was also conventional, with a slight tendency to float.

When the autothrottle was engaged, the workload was drastically reduced, and this is borne out in the Bedford ratings, and the requirement to retrim was liked.

The pilot commented that it would be 'quite a shock' transitioning to the unaugmented aircraft. The problem would be stabilising the flight path and pitch attitude, and the loss of the autothrottle would also make the task more difficult. Concurrency flying would be required.

In general, this law was semi-conventional in nature, assisted by the requirement to trim to speed. However, the benefits provided by flight path stability resulted in the aircraft being slightly non-conventional, and it was not as nice as the pitch rate with speed feedback law to fly.

Normal acceleration with angle of attack stability

This law was again flown by one pilot. As before, problems were experienced with the slow trim rate. The aircraft response during flap deployment was conventional, with light to moderate forces, but the slow trim rate hindered the task.

The control forces were also light and appropriate during the approach, with reasonable short term dynamics. As before, the slow trim did not help with the task. The flight path hold characteristics were favourable, and no problems were experienced with pitch attitude / flight path consonance.

The pilot who flew this law considered the flare to be 'nice'. Initially he overflared, but by releasing the back pressure slightly he was able to lower the pitch attitude and land where he wanted to. He commented that it was nice to be able to do that, and the configuration was not PIO prone. No problems were experienced with airspeed control.

The primary effect of the autothrottle was to reduce the workload, and it had quite a large effect with this configuration. The pilot made the comment here that he would have preferred to chop the power manually.

In the failure case, the difference between this aircraft and the baseline would not be too large. The pilot would probably be frustrated since he would not be able to fly as tightly as before, but could fly the baseline every few months and still be safe.

In general, this law was semi-conventional, but it was hindered by the slow trim rate.

6.8.2 General Comments

The following comments were also made generally, or where more than one law was concerned.

Display Design

Comments were made about the displays, and were concerned with the following two areas. The first was the speed scale tape. Two pilots commented on the difficulty with using the tape, which was only made easier by the speed trend vector implemented.

The second main area of comment, which was made by all of the evaluation pilots was the lack of a flight path vector. These comments originated with the normal acceleration law, and the pilots wanted this vector to confirm the flight path. This type of display is relatively straightforward to design in theory, even if it has to be quickened by T_{θ_2}, but in practice it is susceptible to turbulence and other atmospheric effects which can make is difficult to use and distracting, and therefore can be misleading.

Speed and Energy Awareness

Pilots comments were recorded concerning speed and energy awareness. The energy awareness was increased through the throttle position, and the lack of moving throttles with the autopilot significantly reduced the energy awareness.

The speed awareness came from two main sources. The first was from the requirement to trim, especially with the trim to speed laws. The second source of information to assist with speed awareness came from the trim to speed bug. The speed at which the reference speed for the speed stability laws was displayed on the airspeed tape as a bug. One pilot in particular thought that this heightened the speed awareness since he could see exactly what speed he was trimmed at, and rated this as a very positive feature.

Chapter 7

Discussion

This chapter contains the discussion of the results. It has been divided into discussion concerning the control laws themselves, and how they correspond to the criteria, and related discussion, including human factors and cultural aspects.

7.1 Limitations of the evaluations

As previously stated, these evaluations were carried out in a fixed-base simulator with night visual graphics. This leads to some inherent limitations. Firstly, the lack of motion in the simulator can be a little misleading for an inexperienced evaluation pilot since the cues which are associated with motion are missing, which may lead to problems with flight path control. However, the pilots used for these evaluations were experienced in the use of fixed-base simulation for handling qualities investigations, which would have reduced the effects due to the lack of motion to a minimum.

Secondly, the limited night visual graphics combined with a limited field of view (no more than 50 degrees from the centre of the picture on one side, and approximately 30 degrees on the other) resulted in a lack of cues to the aircraft sink rate, especially in the flare, which meant that most of the landings could, at best, be classified as hard. The lack of a touchdown jolt also did not assist in the perception of the sink rate at touchdown.

Finally, the fact that these investigations were not being carried out in flight reduced the anxiety associated with flight, and this would have had an effect on the evaluations.

The lack of moving throttles during autothrottle operation caused some reduction in pilot energy awareness. Unfortunately the throttles had to be non-moving due to the simulator hardware setup. This was probably a factor in some of the autothrottle evaluations. In addition, one pilot (who is actually the development pilot for the aircraft under consideration) commented on the high throttle movement to thrust gearing, which was excessive. This may have caused problems in speed control for some of the other pilots, although it was constant throughout the evaluations.

Atmospheric disturbances were not included since the idea for these evaluations was to isolate the basic characteristics of the control laws. However, the design of good control laws which are resistant to atmospheric disturbances is not a trivial task, and will need to be considered for later studies.

Due to the limited length of the evaluation sessions, the evaluations had to be performed reasonably quickly. This did not cause too many problems for these evaluations, but when the number of control laws is reduced, longer evaluations for each law will be feasible.

7.2 Piloting Technique

A study of this set of evaluations, and also of comment cards from previous programmes [30] showed that the laws which gave the best performance were those where the pilot used a classical control technique. This does not mean that the aircraft dynamics were classical in nature, solely that classical control techniques could be used with these dynamics. Classical control techniques may be used with classical aircraft dynamics, and also with pitch rate, C*, and the forms of these control laws with induced static stability for the approach and landing task. Classical control techniques may also be used with a normal acceleration law, but this is more limited since they can produce frustrating results for some reconfiguration tasks due to undesirable pitching motions, and they are also non-conventional for a non-stabilised speed approach, where the aircraft will pitch up as it slows down with no pilot input to maintain the glideslope.

For the purposes of this trial, classical control technique has been defined as an attitude stabilisation technique. The pilot selects a pitch attitude which he thinks will give the desired flight path angle at the desired speed. Perceived errors in flight path angle are then corrected for by modifying the desired pitch attitude by the appropriate correction. The aircraft is flown in this way because pitch attitude is visible, and the pilot is able to enter a tight control loop to maintain it due to the dynamics of the configuration. The pilot is not able to enter this tight loop control with flight path angle. Firstly the flight path response is not directly visible since the instruments which display it in a conventional cockpit are subject to lags. In addition, the flight path response lags behind the pitch attitude response by T_{θ_2}, which results in more lag which prevents the pilot from entering tight closed loop control.

A classical aircraft will pitch and heave in the short term due to the initial aircraft response, and then the long term effects will be dominated by the static stability.

The characteristics of the different control laws in various reconfiguration tasks can be seen as follows. The data for the desired responses was determined from a series of handling trials carried out in training simulators of a number of transport aircraft [2]. They were all carried out by a single evaluation pilot. In general, the aircraft response must be linear, predictable and in the correct sense, and these aspects are discussed for the different control laws shown here.

Thrust Change

Classical aircraft generally respond in different ways to thrust changes, depending on the engine location. The desired response to an open loop thrust reduction this case is either no short term response, followed by a pitch down to maintain speed as the static stability effects take over, or a slight pitch down as the power is reduced, which will tend to maintain airspeed in any case.

The flight path may decrease slightly as the aircraft maintains attitude, and then drop as the aircraft lowers its nose to maintain airspeed. A pitch up is not desirable since a classical aircraft will then reverse the direction of the pitch up as the speed drops off, which is not suitable from a predictability point of view. This pitch up will also result in a change of direction of the flight path response, from an initial slight climb, to a final descent.

For the configurations considered here, The augmented aircraft (law 1) will respond as the baseline aircraft does. Having under-wing engines, this aircraft tends to pitch down when thrust is reduced and vice-versa, which is a desirable response. The addition of the stability augmentation system will not change this response. The pitch rate demand or C* control laws will tend to maintain pitch attitude, and therefore they will give no perceived attitude response. However, as the speed reduces, the amount of lift will change, and the aircraft will start to descend until the increased angle of attack is sufficient to maintain the achieved current rate of descent at the new airspeed. Therefore there is no perceptible pitch response, but the flight path responds in a conventional manner. For a normal acceleration demand system, the aircraft will pitch up as the airspeed reduces in an attempt to maintain lift to hold the aircraft flight path. This is unconventional since it is in the opposite direction to a classical aircraft response.

With induced speed stability (through trimming to an airspeed or angle of attack reference), the pitch rate system will initially not respond, and then pitch down to maintain the desired airspeed or angle of attack, which again is a classical response. A normal acceleration demand system with an airspeed or angle of attack trim system will behave differently. Depending on the 'level' of the airspeed or angle of attack stability, the aircraft will initially pitch up to maintain its flight path, and then pitch down to attempt to revert back to its trimmed airspeed or angle of attack. This is very undesirable since it is a reversal in direction, which drastically reduces the predictability of the response.

From the point of view of transitioning from the augmented aircraft to the unaugmented aircraft, the augmented aircraft or the pitch rate system produce essentially classical responses, though the pitch rate system with induced static stability is more conventional than the pitch rate system with no static stability. The normal acceleration system produces an unconventional response which is undesirable. The most undesirable response is the normal acceleration system with artificial static stability since the response is not classical, and there is also a reversal in direction of the response.

Airbrake deployment

As with thrust changes, classical aircraft respond in different ways to airbrake deployment. Depending on the location of the airbrakes, they will produce different responses. For example, tail-mounted petal airbrakes such as those on the Avro RJ produce a drag increase with no noticeable pitching moment since they do not interfere with either the wing or tail aerodynamics. However, wing mounted airbrakes (as upper surface spoilers) often produce a pitching motion, either nose up or nose down, depending on their location on the wing. From Field's work, the desirable response is either no pitching response or a slight pitch down to enable the airspeed to be maintained. A nose up pitching motion is undesirable since it will cause the speed to decrease even more.

Again, with the configurations considered here, the augmented aircraft will tend to pitch in the same direction as the unaugmented aircraft. For a tail mounted airbrake, this tends to be little motion, for a wing mounted system, this tends to be a slight nose down motion. The pitch rate or

C* systems will hold pitch attitude, causing the aircraft to slow down and the flight path angle to decrease, which is the same as the classical aircraft response with a aft fuselage mounted airbrake. With wing mounted airbrakes, the pitch attitude will be maintained, but the aircraft angle of attack will increase to a greater value than with the tail mounted airbrake due to the loss of lift caused by the airbrake. For a normal acceleration system, the aircraft will pitch up as the aircraft slows down after airbrake deployment due to the requirement for an increased angle of attack to maintain lift. This results in the aircraft slowing more, and the aircraft continuing to pitch up. This pitch up is in the wrong sense for a classical aircraft.

With static stability, the pitch rate system will pitch down as the speed or angle of attack change in an attempt to maintain them, which is a classical response. As with the power changes, the normal acceleration system will initially pitch up to maintain flight path, and then pitch down to revert back to the trimmed angle of attack or airspeed, again producing a change in response direction, which is undesirable.

Again, the pitch rate system will behave in a similar manner to the unaugmented aircraft. The pitch rate systems with static stability behave in an almost identical manner to the unaugmented aircraft, while the normal acceleration systems behave in the opposite manner to the unaugmented aircraft.

Gear deployment

The characteristics for gear deployment are similar to those for airbrake deployment, only the magnitude of the change should be much less, if any. The desired responses are the same as for the airbrake deployment, and the responses of the different configurations will be the same as for the tail-mounted airbrake deployment.

Flap deployment

Flap deployment characteristics tend to be significantly different from one aircraft to another due to the major change in aerodynamics as the flaps deploy. Flap deployment responses may give considerable pitching or heaving, and they may be considerably non-linear. A pitch down response is more desirable than pitch up since this will help to maintain airspeed, and it will also reduce the pitch attitude, which will help to keep the flight path angle constant since the lift will remain constant due to the wing angle of attack reducing, giving a more or less unchanged lift coefficient.

A classical aircraft may therefore respond in any form. The response characteristic is generally dependent of the trim change experienced, although the trim changes are generally automated so that the pilot does not need to retrim as the flaps move. The unaugmented aircraft under consideration here tends to maintain pitch attitude during flap deployment, requiring forward wheel motion and trim to restabilise the flight path. A pitch rate or C* demand system will tend to have a similar characteristic, although the longer term nose down pitching motion of the classical aircraft attempting to return to speed will not be present. A normal acceleration system will tend to reduce pitch attitude in order to maintain flight path, which is a classical response, and as desirable as the zero attitude response of the pitch rate demand system.

Therefore either system with speed stability will reduce the aircraft pitch attitude to maintain airspeed for no thrust change as the drag increases due to the flap deployment. For a pitch rate demand system with angle of attack based static stability would produce no initial response, followed by a pitch-up motion, which would increase the pitch attitude to take account of the increase in lift increasing the flight path angle, and therefore reducing the angle of attack at a fixed pitch attitude. This assumes a small speed change. For a large reduction in airspeed, there may be no significant long term behaviour, but trials in the flight simulator showed that a large reduction in airspeed was required to offset this, requiring a power reduction. The normal acceleration demand system will initially produce a slight pitch down motion to maintain the flight path angle, and then pitch back up as the system tries to revert to the trimmed angle of attack, which is a reversal in pitching motion, and therefore undesirable.

In this case, either the pitch rate or normal acceleration demand system have similar characteristics to the unaugmented aircraft, and both systems give short term responses which are essentially classical in nature. Static stability induced by speed reference systems give longer term responses which are closer to a classical aircraft with an automatic trimming system, while static stability induced through angle of attack reference systems give undesirable motions, as they may do in an unaugmented aircraft, which would require an automatic trimming system.

General comments

The previous paragraphs show that the pitch rate based demand systems give essentially classical responses which are similar to those for the unaugmented aircraft in the short term, and the introduction of speed based static stability gives classical long term responses. Normal acceleration demand systems give non-classical responses, often in the opposite direction to a classical aircraft, with static stability sometimes giving a reversal in the direction of the aircraft pitch attitude response, which is undesirable due to lack of predictability.

Field also found that the absence of trim changes with speed are mildly frustrating to the pilot in the A320, especially where the pilot felt as though he should be trimming. He found that the requirement to trim with configuration change in the short term, and particularly speed changes in the longer term are a useful and positive cue to the pilot.

7.3 Aircraft Dynamics

A number of contempory handling qualities requirements were used on the unaugmented aircraft in order to determine the aircraft characteristics, and the degree of compensation needed.

Analysis of the basic aircraft using the Neal-Smith criterion, modified for transport by Mooij showed that the unaugmented aircraft requires a large amount of lead correction at low speed, of the order of 80 to 90 degrees for some cases, which renders it level 2. This was confirmed by these evaluations. All of the control laws were designed to give a constant value of 'effective CAP', and they all had similar values of Neal-Smith compensation, although the normal acceleration laws required a few degrees less lag than the rest due to their slow dynamics.

The short term mode natural frequencies for pitch rate, C* and angle of attack were higher than those for the normal acceleration control laws. This has been seen before, but not explained. The author believes that it is due, in this case, to having to design for a constant value of GCAP, and this is borne out by the evaluations, as none of laws 1-7 received any serious complaints about the characteristics of the response. Therefore the use of a Generic CAP value as a design tool has been borne out here.

Since the normal acceleration laws have a lower short term mode natural frequency than the other laws for a constant value of GCAP, they have a reduced bandwidth. This can be seen in figure 4.6, where the normal acceleration laws are the ones which are just inside the level 1 limits. This has interesting consequences for the Bandwidth criteria. Since most of the work performed in aircraft handling has concentrated on conventional and pitch rate configurations, the bandwidth criterion has been developed from these. This work shows that the bandwidth criterion boundaries must be recalculated for each law since comparable dynamics (i.e. constant GCAP values) in different laws have different short term mode natural frequencies and therefore different bandwidth values.

However, this does not mean that Bandwidth is invalid. There may be a requirement to place lower limits on the bandwidth for a particular task, for example air to air refuelling. This was briefly attempted in the simulator, though not as a formal part of this study. The lower bandwidth in the normal acceleration law was noticeable through the slower response dynamics compared to the pitch rate or angle of attack configurations, since the normal acceleration response was much slower, and the task was much more difficult when trying to fly the receiver close to the tanker. When the receiver was a little further back from the tanker, the noticeable difference between the two laws was much less. Therefore there may be a lower bandwidth value for every task, and certain control laws may not be acceptable for that task because they cannot achieve a sufficiently high bandwidth with acceptable response dynamics. Therefore the correct design procedure would be design for the response dynamics (i.e. GCAP), and check the bandwidth obtained is sufficient for the task. This effect was also demonstrated during these evaluations. One pilot thought that the normal acceleration law may have been PIO prone in the flare, but after a couple of attempts to land the aircraft decided that it wasn't. The steady state forces in the flare were very close to those of the other pure rate laws with attitude-type response dynamics in the flare, and therefore it is postulated that this 'ghost PIO tendency' was due to the lower bandwidth of this law.

The GCAP work also explains why CAP, in its conventional form has been reasonably successful with the pitch rate response type. Analysis of table 4.6 shows that for a reasonably constant value of GCAP, the short term mode natural frequencies of the angle of attack and pitch rate systems are more or less identical. There is one caveat here though - all of the control laws used for this evaluation were designed using a proportional + integral controller, and using a second order mode with a 0.7 damping ratio as the short term mode response. If the short term mode response had first order characteristics then CAP probably could not be applied.

Many evaluations have been carried out using pole placement methods. These enable a wide range of response characteristics to be examined. However, they can have problems. Analysis of previous studies carried out showed that no account was taken of dropback, and in some cases there were excessive amounts of dropback ($\pm$ 10, where the limits proposed by Mooij are approximately -0 +1.5). Therefore this could have clouded the results. However, limits were specified on dropback for these laws.

In summary, a small amount of dropback (0.5) in the landing configuration reduces the effective flight path delay parameter (t_γ), which seemed to assist the pilot in the flight path control task.

Indeed, this was incorporated in all of the laws, and no problems were experienced with the pitch attitude to flight path consonance. Therefore dropback is justified as a criterion for use in the design process as it helps to fine tune the flight path response.

No other problems were experienced with the value of the short term mode damping ratio selected, and therefore 0.7 seems to be a suitable value.

The long term dynamics were not explicitly specified in the design process, although it was verified that they were stable. It seems that the value of about 3.2 knots per pound stick force was suitable for the approach - it gives the pilot some feel that he is off speed, yet does not give a long term mode frequency which is excessive (approximately 12 times slower than the short term mode, which is a suitable separation), and does not seem to be high enough to degrade the glideslope tracking as NLR found (see section 2.2).

No problems were experienced with short term Pilot Induced Oscillations. Several pilots found that there was a long term oscillation with the autothrottle engaged due to the sensitive nature of the autothottle, though this was not deemed to be dangerous. This is to be expected since all of the laws meet the published phase rate criterion which has been shown to be a good indicator of PIOs, see figure 4.8.

7.4 Static margin and manoeuvre margin requirements

For a classical aircraft, the distance between the static margin and manoeuvre margin is more or less independent of the CG position. Therefore as the centre of gravity position is moved aft, the static margin and manoeuvre margin both decrease. At the stick fixed neutral point, the static margin is zero, and therefore the aircraft will not try and reject angle of attack disturbances by returning to the trimmed angle of attack.

Static margin and manoeuvre margin are related by the following equation. It can be simplified as following for a conventional aircraft.

$$Manoeuvre\ Margin \approx Static\ Margin + Pitch\ Damping \tag{7.1}$$

For an unconventional response type, the classical relationship between static and manoeuvre margin is modified. For a pitch rate demand system, the static stability of the configuration is zero, i.e. the aircraft will not try and return to a trimmed angle of attack. The pilot can perceive this through the nature of the aircraft response. However, he can still see an effective 'manoeuvre margin', which comes directly from the CAP analysis for unconventional response types (GCAP analysis). CAP can be shown to be proportional to the aircraft manoeuvre margin for a classical configuration, and therefore GCAP will probably be perceived by the pilot as an effective manoeuvre margin for unconventional response types. The lack of contribution of effective static margin to the effective manoeuvre margin, assuming classical aircraft dynamics is therefore made up by pitch damping. This is a reasonable assumption for a pitch rate demand system since it will strongly resist attitude disturbances, thus has high pitch rate damping. Other systems such as C* and normal acceleration will also produce improved pitch rate damping.

Consider how the pilot would see these changes in manoeuvre margin and static margin. He will see the manoeuvre margin through changes to the short period response characteristics for a classical aircraft, and this should be unchanged for a non-conventional response type. The CAP criterion was originally developed as a closed loop flight path control criterion, and any problems with the flight path control would be apparent to the pilot. The evaluations performed here have shown that the lack of speed stability does not necessarily reduce the ability of the pilot to control airspeed since the configurations which give zero static stability have much improved pitch attitude dynamics, although his speed awareness is reduced. In some cases, greater airspeed control performance was achieved through the improved response dynamics (basically an increased manoeuvre margin) making the attitude control task easier, and therefore the pilot has more spare capacity to devote to airspeed control.

The use of manoeuvre margin for handling qualities of non-conventional response types is therefore suitable, and this has been demonstrated through the use of GCAP. The use of static margin is not as applicable to non-conventional response types due to the breakdown in the classical relationship between manoeuvre margin and static margin. The characteristics of a conventional aircraft with reduced static margin can be reproduced with the FBW laws considered here, and can produce improved handling qualities over the baseline aircraft due to improved response dynamics.

The requirement for a specified static margin is still valid however. Improvements to pilot speed awareness can be made through the use of airspeed or angle of attack feedback, and this implies the introduction of an artificial static margin to a response characteristic with zero static margin. The use of either of these feedbacks will give the pilot the awareness that the aircraft has positive static stability, although airspeed feedback does not give static stability in the true sense of the word.

FAR 25.173 has a static longitudinal stability requirement for transport aircraft. The conditions under which this apply are listed in FAR 25.175. The results of the handling qualities evaluations here have shown that this is not required for non-conventional response types as an acceptable manoeuvre margin can be obtained without the need for static stability. It is postulated that since non-conventional response types were not under consideration when FAR 25 was written, they were not considered. This FAR needs redefining in terms of non-classical aircraft dynamics. It is also said that the static stability requirement was developed as a result of a manoeuvre stability requirement, and the demonstration of static stability was more straightforward for the FAR 25 [40] description. The only requirement for dynamic stability is that the short period oscillations must be heavily damped (FAR 25.181), with controls both free and fixed.

It is also proposed that a classical response type in this context is considered to be one where the classical relationship between static and manoeuvre stability is maintained.

7.5 Trimming Issues

Some of the configurations flown for these evaluations did not require trimming, and others required trimming in a non-conventional sense, i.e. trim to speed. In order to keep the pilot in the loop, it is necessary to make him do something. This needs to be similar to what he would do in a classical aircraft since it has already been stated that this limits the possible designs. Trim changes with speed are desirable since the pilot needs to be aware of speed at all times during manual flight. In addition, the stick force gives him some idea as to how far away from the reference speed he is. Trim changes with flight path angle and aircraft configuration change are less desirable since they tell the pilot that something has changed, but do not generally give him an idea as to how far away he is from a particular point. Therefore it seems desirable to have the pilot trim to speed since he gets both change and actual state information, which is consistent across the flight envelope. In addition, the majority of the major trim changes are due to speed changes.

According to Field, the most desirable cues for flap deployment from pilot's flying either a conventional aircraft or a fly-by-wire aircraft equipped with sidesticks are flap lever position, the flap indicator position and an ECAM warning when the aircraft is not correctly configured. The desirability due to stick force, stick position and flight path or aircraft attitude change are less. Therefore it seems that the desirability of trimming with aircraft configuration is a less important method of telling the pilot that the flaps are deployed.

Therefore for a civil aircraft, a speed trimming strategy should be desirable, and this was confirmed very strongly by one pilot, especially due to the bug which was used to highlight the current speed reference.

7.6 Control Law Mode Transition under Failure

This subject is very closely linked to motor skills, and therefore these warrant mention. The subject of motor skills is vast, however there are some relevant points to be learnt. It is considered relatively easy to maintain two very different motor skills such as flying an aircraft and driving a car. It is also considered relatively straightforward to maintain a skill when one has many thousands of hours using that skill. One example of this is an experienced driver or airline captain, who will not have to fly as much as a very junior or inexperienced pilot / driver to maintain proficiency. However, it is very difficult to maintain two similar skills, such as flying two aircraft which are quite close, such as a large aircraft and a small light aircraft, or an aircraft where two different piloting techniques are required since they can become confused within the mind of the pilot.

This was one reason why the handling qualities of the Tornado have been designed in the manner that they have. The Tornado is a fly-by-wire aircraft, with an element of manual reversion. After the manual reversion was deemed necessary, it was decided that differences between the handling of the aircraft in the fly-by-wire mode and the direct mode should not be significantly different since if they were, the pilot would effectively have to fly two different aircraft at the same time, and in emergency situations, where failures were occurring and the pilot would be under a very high workload, he could adopt an incorrect control strategy. Therefore the handling qualities of the two modes should be comparable.

This can be found from the results of the evaluations carried out here. In descending order of difficulty, the following comments were made.

- **Angle of Attack** In going from the normal to the direct mode, the pilot would have little difficulty, except that the direct law aircraft is very much looser in attitude.

- **Pitch rate or C* with speed reference** The pilot would have some more trouble than angle of attack due to the very desirable nature of these control laws, and he would be frustrated with the deficiencies in the trimming system as well as the lack of attitude solidity with the basic aircraft. However, the pitch rate response characteristic is still comparable with a conventional aircraft.

- **Pitch rate or C*** The pilot would have more trouble than before, mainly having to learn to retrim the aircraft very quickly, and also due to the lack of solidity in attitude. However, the pitch rate response characteristic is still comparable with a conventional aircraft.

  close, such as a large aircraft and a small light aircraft, or an aircraft where two different piloting techniques are required since they can become confused

- **Normal acceleration** The pilot would have the most trouble with this aircraft due to the normal acceleration response type being different to the pitch rate-like behaviour of a classical aircraft, and also due to the fact that he would have to learn to retrim.

These comments do not mean that any of the laws are bad in any way, indeed the Cooper Harper ratings show this not to be the case. However, they do indicate that in emergency situations, the pilots would have more problems reverting to the normal acceleration or pitch rate / C* response types as opposed to the C*U / qU or angle of attack response types.

Another characteristic of human behaviour can be described as 'revert to type' where a pilot will revert to the systems which he knows the best. For a low time airline pilot, this will be almost certainly a classical aircraft type behaviour since he will have learnt to fly on this type of aircraft.

In summary, this section states that the fly-by-wire law should be something like classical in nature, not because the other response types give particularly bad handling qualities, but because the aircraft needs to be flyable in the presence of the past experience of its pilots, and there should be no significant changes in the handling qualities in failure situations, where 'direct' control laws tend to be used, i.e. the aircraft behave in a classical nature.

Work has been performed as a part of a GARTEUR Action Group to investigate handling qualities for future transport aircraft [45]. One of the main conclusions from this work was that the changeover from primary to backup systems at flight control system failure should not result in a large step increase in workload and pilot compensation, and the degradation in system sophistication should be acceptable by the pilot. This backs up the findings in this study, where the systems where the transition is easiest from primary to backup have the lowest change in handling characteristics.

7.7 Human factors discussion

This section briefly considers human centred design principles, and their applicability to control law design. It is important to consider these aspects since the more important principles may not come out through the evaluations performed due to the nature of the pilot's used, or the simulation environment used.

7.7.1 Parameter Awareness

As a general rule, pilot's like to see what they are controlling, and this was demonstrated in some of the control law evaluations. For example, one comment concerning the normal acceleration law stated that the pilot was using the vertical speed indicator to give him a measure of flight path angle, which was not ideal for the task. Some form of flight path vector display, which would actually give the aircraft's current flight path vector, as used on the A320, would have been appropriate.

This illustrates some of the problems experienced with non-conventional control laws. The problems do not arise as much with a pitch rate command system since pitch attitude is always observable, either from the 'real world horizon' if the pilot is flying 'head up', or from the artificial horizon / attitude indicator if the pilot is flying 'head down', especially as it is one of the largest and possibly most compelling instruments.

One design goal should be to keep the pilot 'head up and eyeballs out' for as much time as possible. This ensures that he can keep a good look out for conflicting traffic in the currently congested airspace. As a result of this he can always observe the pitch attitude, even if the real world horizon is not as clear as it might be. However, for a system where the pilot is primarily controlling flight path, the flight path is not directly visible to the pilot, which would necessitate some form of Head Up Display if he is to be able to observe it.

7.7.2 Speed Awareness

It has often been said that if you want the pilot to be situationally aware of something, make him operate something which is dependent on that event. One example of this is speed control, where a conventional aircraft generally needs to be trimmed as the speed changes. This keeps the pilot in the speed control loop, and makes him aware of the current speed simply due to the fact that he needs to trim, and once he is in trim, any variations from the 'reference speed' will be demonstrated through a constant force which must be held to maintain the off-trim speed.

7.7.3 Training Issues

Pilot's are taught to fly on instruments by stabilising the aircraft in attitude. This is because changes in flight path are slow to manifest, and therefore the pilot cannot control them tightly. In order to do this, the pilot uses a surrogate cue, usually pitch attitude, which he can control tightly. The flight path angle for a conventional aircraft will lag the aircraft attitude by T_{θ_2}. Therefore it would seem that the most suitable control strategy is an attitude strategy, and this corresponds to the technique that pilot's are taught to fly from the start of their flight training. This implies that the pilot needs to be able to accurately control pitch attitude, and therefore a strategy based on pitch attitude stabilisation may be more suitable than flight path stabilisation.

Thus the conventional control technique has been designed to compensate for the deficiencies within the aircraft, namely the flight path lag behind pitch attitude.

7.7.4 Cross Cultural Issues

Cultural differences can also play a part in aircraft design and operation. It has been shown here that the normal acceleration laws enable the pilot to sit back from flying, especially when operating with an autothrottle, whereas the pitch rate based laws with speed stability require the pilot to be in the loop at all times, as with a conventional aircraft. This, according to Merritt [46] is due to the cultural differences which exist in the national design teams. Boeing aircraft, which are built in the USA, are built to give the pilot more perceived (closed loop) control, whereas the flight control systems for Airbus aircraft are built in France, which is a nation where there is more of a role-based (i.e. the Captain is the boss) and hierarchical structure than in the USA. Therefore the role takes priority over individual concerns, and the Aircraft is designed to function as perfectly in its role as possible, with minimal interference from outside sources (i.e. pilots). Merritt states that this is controversial, it illustrates the effect that culture can have, and can have consequences when an aircraft designed with one culture in mind is operated by another (i.e. American pilots may not like the Airbus because it does not allow then to get in to the loop as an American aircraft would.

There may also be other issues. All pilots currently learn to fly on conventional aircraft, and therefore they can comprehend this. However, pilots from different cultures may have had experienced vastly different amounts of technology. For example, children growing up in many countries have a very high exposure to home computers, whereas in other countries, this will not be the case. Therefore they are less likely to be intimidated by sophistication of technology due to their increased exposure, and may therefore find it easier to accept situations such as flight control system mode changes, where there is an 'aircraft commanded' mode change.

7.7.5 Human Factors Summary

Human factors should consider the following factors for a design

1. The ease of operation
2. The likelihood of pilot error having being reduced to a minimum
3. The appropriate level of complexity
4. The adequacy of feedback provided

The flight deck should accommodate the opinions of a number of operational and test pilots.

The following should also be considered.

1. Differences in operating logic, standard operating procedures, displays and modes which will affect transferability from other types and variants.

2. How much training time pilots will receive, the extent of their technical knowledge which is assumed and any special technical knowledge.
3. Whether the system logic and mode of operation are consistent with expectations / conventions.
4. The feedback to the pilot.
5. Consistency with the other features of the flight deck.
6. Whether the flight crew are in command and in the loop.

7.8 Display design

The displays should be consistent with the command principle in use. The display used for the evaluation is an EFIS display, with a speed tape on the left hand side, and a conventional single pointer aircraft altimeter on the right hand side of the primary display.

Several of the pilots commented on the desirability of a flight path vector, especially for the normal acceleration command systems. This is in line with the philosophy of this control law since it would result in the parameter which is being directly controlled (the flight path angle) being visible to the pilot when his head is in the cockpit.

The display of flight path angle is possible through the use of head up displays, which are now becoming more common in civil aircraft. However flight path vector and head up displays pose special design problems which need to be successfully overcome in their implementation, such as quickening the flight path vector, and removing turbulence effects from it.

For a pitch rate demand system, the aircraft pitch attitude, which is the parameter that is being held is directly visible through the use of either the artificial horizon (head down) or the real world horizon (head up). Therefore this system is maybe more suitable to an aircraft implementation where there is no head up display fitted.

Chapter 8

Conclusions and Recommendations

8.1 Conclusions

This evaluation has shown that it is possible to design a number of control laws based around different philosophies using a set of law independent requirements which were derived from the available literature.

The control law which demanded the lowest workload and received the best Cooper Harper rating was the normal acceleration law, or flight path rate demand law. The pilots liked this due to the low workload and ability to hold flight path during reconfiguration or speed changes. However, it requires a non-conventional piloting technique, and the pilot is more out of the loop than with other configurations. This law also necessitates the implementation of a flight path vector to display the current flight path angle, which may have problems in its implementation. In addition, no turbulence was present during the evaluations, which may also pose a serious problem.

The law which most closely represented a conventional aircraft and also received favourable pilot comment was the pitch rate law with speed feedback. This gave good attitude stability, and the trim to speed gave it a conventional feel, and a good airspeed awareness. The normal acceleration law with speed feedback did not give quite such a conventional feel.

The use of a Generic Control Anticipation Parameter (GCAP) has initially been shown to be successful and applicable to more control laws than previously tried, and further investigation is required in this area. This parameter was demonstrated to explain some of the results of previous investigations.

Although all of the control laws look promising, it is recommended that the augmented angle of attack, Nz-U, qU and Nz laws only are carried forward, since they are the most promising, and seem to offer the most potential.

The use of an autothrottle has a significant effect on the workload for speed control and also speed and energy awareness. The result is favourable for an attitude or flight path stabilisation law, but not so good for augmented angle of attack due to the lack of attitude stability.

An aircraft which handles in a conventional manner is the most suitable from a flight control system failure point of view since it requires the gives the smallest change in aircraft handling characteristics when reverting to the unaugmented aircraft. Currently, the augmented angle of attack and pitch rate with speed feedback laws only give a small change in aircraft handling, while the normal acceleration laws have quite a large transition in the failure case. This transition warrants further examination.

8.2 Recommendations for further work

Turbulence and other atmospheric effects should be considered since they will have an effect of the implementations of individual laws.

A more demanding task, such as a tighter flight path tracking task needs to be tested, and the task assessed as to whether it is a suitable operational requirement.

The use of tactile feedback to the pilots with speed changes such as moving the control column datum position as the trimmed airspeed changes needs to be addressed.

The problems in reverting to the basic aircraft in the flight control system failure case warrant further examination in terms of major handling qualities differences between the augmented and basic airframes, and the problems that this may cause.

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