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Generic regional aircraft flying qualities for the windshear and formation flying tasks

Jim Gautrey

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Volume 1

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Chapter 1

Introduction

This report describes a series of flying qualities investigations designed to look at flying qualities issues associated with fly-by-wire control laws for civil transport aircraft. It follows on from a previous study which considered flying qualities for the reconfiguration, approach and landing tasks [1]. Issues raised during this previous study were followed up and design improvements made to the control laws in order to improve them for this subsequent series of evaluations.

Two different tasks are considered for this series of evaluations for the following reasons. Firstly, the control laws were only evaluated between airspeeds of 140 knots and 121 knots for the approach and then to approximately 115 knots in the flare during the previous set of evaluations [1]. This obviously does not cover the entire aircraft airspeed range, but since the approach and landing task is generally accepted to be the most critical task for a civil aircraft, it is deemed a suitable task for evaluating the control laws under consideration.

However, civil aircraft manufacturers generally use other tasks for the evaluation of control laws since there is a requirement to test the laws over the full flight envelope. For example, several different tasks were used for evaluation during the design of the Boeing 777, including a variety of approach tasks, en-route tasks, and in-flight tracking type tasks.

A formation flying task was therefore proposed as a suitable task for evaluating control law performance at altitude for the generic regional aircraft. It was initially thought to be a tight flight path control task, and this was quickly confirmed from a brief trial prior to the main evaluations. In addition, this task is one which is the most demanding for a large military aircraft since it requires precision control of both flight path and airspeed. Finally, it is becoming more and more common to use modified civil aircraft in either the military transport or in-flight refuelling roles, with the Vickers VC-10 and Lockheed L-1101 being used as in-flight refuelling receivers and tankers and the Nimrod (Military Comet) as a receiver in the Royal Air Force alone.

It was also decided to consider atmospheric effects. Initially, it was proposed to consider the effects of both windshear and turbulence, but evaluations in turbulent conditions were later dropped since its main effect is in the longitudinal (airspeed) axis, with effects in the longitudinal (pitch) axis being limited by the effects of the control laws. In addition it did not give repeatable results. However windshear, which here is taken to represent a decreasing headwind, is a flight path control problem (see section 2.1) since it causes an effective change in aircraft flight path angle, and it was found to be a much more suitable task.

1.1 Scope of the evaluation

Six control laws were considered for these evaluations, and these are listed as follows.

1. Unaugmented aircraft. This was retained as a baseline, having being used in this manner in the previous study. No longitudinal augmentation is used for this configuration.
2. Augmented angle of attack. This configuration was retained since it is the simplest augmented fly-by-wire solution, and gave a good conventional response in the last series of evaluations. The stick is still effectively connected directly to the elevators, with the control law (acting as a pitch damper) inputs being summed in parallel, in the same manner as a yaw damper.
3. Pitch rate demand with trim to airspeed. This law was retained since it showed promise as a conventional control law. At a constant airspeed, and with no pilot input, the control law maintains a constant pitch attitude.
4. Normal acceleration demand. This was retained since it had the best ratings of all of the configurations from the previous evaluations. It is the only law being evaluated for this set of evaluations which does not have any form of trimming requirement, and has effectively neutral static stability. It is the control law used on the Airbus A320, A330 and A340 aircraft.
5. Normal acceleration demand with trim to airspeed. This was retained since it showed the beneficial nature of flight path stability, and still retained conventional flying qualities due to the requirement to trim to airspeed. It is the type of control law used on the Boeing 777.
6. Normal acceleration demand with trim to angle of attack. This was retained since it showed promise, but did not receive a fair evaluation in the previous set of investigations [1] due to an inappropriate trim rate. It is typically used in modern fly-by-wire fighter aircraft, albeit with modifications depending on the aircraft's airspeed and configuration .

All of the control laws will be evaluated for both the windshear and the formation tasks. The design process used to obtain the control laws is highlighted in chapter 3.

A limited number of laws were considered in comparison to the previous evaluations to limit the amount of simulator and pilot time required, and the decision concerning which laws to include was made as a result of the previous set of evaluations [1].

The following objectives were set.

1. To build on the results of the previous series of evaluations[1], and to correct any minor deficiencies which became apparent during those evaluations.

2. To assess the nature of the control laws for a tighter flight path control task than the longitudinal offset approach and landing task used previously, through a windshear penetration task.
3. To confirm the results of the previous set of evaluations.
4. To make improvements to the aircraft feel system, including adding datuming with trim movement for the fly-by-wire laws.

1.2 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 for the evaluation.

Appendix E contains the pilot comment card.

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

Chapter 2

Background and Theory

This chapter contains the background and theory for the current set of flying qualities evaluations. The information is supplied for completeness, but for a more detailed description of the flying qualities criteria used, see reference [1].

2.1 Effects of Windshear

This section demonstrates how the effects of windshear (which for the purposes of these evaluations is a horizontal wind gradient) affects the performance of the aircraft.

2.1.1 Derivation

Consider an aircraft flying through windshear whilst established on an Instrument Landing System (ILS). The pilot (or autopilot / autoland system) will attempt to maintain the airspeed at an appropriate value (nominally $V_{REF} + 5$ knots) and also on the glideslope in the presence of disturbances.

The ILS glideslope and localiser define a flight path with respect to the earth reference frame, and the inertial (or earth) position of this path is not dependent on the local wind velocity or direction, and the pilot will attempt to maintain this inertial path in the presence of disturbances. However, the pilot will see the effect of a steady wind in the difference between airspeed and groundspeed, and also heading angle and track angles. For example, if the aircraft is flying in straight and level flight directly into a 10 knot headwind, the groundspeed will be equivalent to the airspeed, less 10 knots due to the wind effect.

The effect of the wind on the effective flight path angle can be found in the following derivation. The effective flight path angle is the inertial flight path angle which the aircraft would follow if it was flying in zero wind conditions, given it was flying along an actual inertial flight path angle in the presence of a specified headwind and a specified wind shear. Firstly, Newton's second law states :

$$Force = Mass \ \times \ Acceleration \tag{2.1}$$

In this case, the acceleration and mass are measured in the inertial frame, i.e. earth reference frame, and all forces and accelerations must be resolved with respect to this reference frame. This is a fundamental fact, which has important consequences on the aircraft during windshear, since the effects of wind effectively disconnect the airspeed from its inertial speed (or groundspeed).

Using the above information, it becomes apparent that as the headwind component decreases, the airspeed decreases for a constant inertial or earth reference (ground) speed. Since the pilot is attempting to hold a constant airspeed, he will therefore need to accelerate the aircraft with respect to the inertial reference (i.e. the earth) to maintain the airspeed.

Resolving the forces along the flight path,

$$Acceleration = \frac{ResultantForce}{Mass} \tag{2.2}$$

Therefore

$$\dot{V_{air}} + \dot{W_X} = \frac{T - D - mg \ sin\gamma_i}{m} = Groun\dot{d}speed \tag{2.3}$$

$$\dot{V_{air}} + \dot{W_X} = \frac{T - D}{m} - g\gamma_i \tag{2.4}$$

where T is the thrust and D is the drag, both assumed to act along the flight path. m is the mass, V_{air} is the airspeed, W_X is the horizontal headwind, and is assumed to be parallel to the direction of flight, and γ_i is the earth reference flight path angle. This effectively states that the aircraft must be accelerated in the earth reference frame at the same rate as the headwind component decreases to maintain airspeed ($\dot{V_{air}} = 0$).

Therefore, in straight and level, unaccelerated flight,

$$\dot{V_{air}} = \frac{T - D}{m} = 0 \tag{2.5}$$

Therefore, for constant airspeed, thrust and drag and for a non-zero horizontal wind gradient,

$$\dot{W_X} = -g\gamma_{esh} \tag{2.6}$$

where γ_{esh} is the change in effective inertial flight path angle due to the wind shear, or in other words, the aircraft will descend in the inertial frame in the presence of wind gradient, compared to the basic airframe. This then gives an effective inertial flight path angle which must be maintained to penetrate the wind gradient.

Consider the next case, with a steady headwind gradient. It can be shown that in order to follow an effective earth reference flight path, the aircraft must follow an aircraft-reference flight path, according to the following formula.

$$\gamma_{est} = \gamma_i \times \left(1 - \frac{W_X}{V_{air}}\right) \tag{2.7}$$

In the limiting case, where the headwind has the same magnitude as the airspeed, the effective flight path angle will be zero, since the aircraft will not be descending, while the earth reference flight path angle will still be as before (-3 degrees for an ILS), since the aircraft will not be making any horizontal progress.

Therefore the effective aircraft flight path angle is the sum of the previous two components.

$$\gamma_{eff} = \gamma_{est} + \gamma_{esh} \tag{2.8}$$

i.e.

$$\gamma_{eff} = \gamma_i \times \left(1 - \frac{W_X}{V_{air}}\right) - \frac{\dot{W}_X}{g} \tag{2.9}$$

Therefore, for a given steady-state headwind, a given required inertial flight path angle and a given wind shear rate, the effective flight path angle may be calculated, i.e. the flight path angle that the aircraft would fly along if the aircraft was removed from the headwind / wind shear condition, and placed in a stationary atmosphere with an identical airspeed and power setting.

2.2 Flying Qualities Criteria

A number of flying qualities criteria were used for the evaluations. Most were initially described in the preceding evaluations [1] and therefore the description of these has been limited to a brief description of the criteria. For the criteria which were not described in the first set of evaluations, a more comprehensive description has been included.

2.2.1 Neal-Smith

Neal-Smith was originally developed by Neal and Smith in the early 1970's [2]. It is a criterion which calculates the amount of compensation that a pilot is required to make to achieve a specified performance. This is generally expressed in terms of a stated amount of phase compensation which gives an indication of the amount of compensation a pilot needs to make to achieve desired performance. An assumed pilot model is used, and it is the variation of the parameters of this model which is used to calculate the required compensation.

Limits are then placed on the amount of compensation that the pilot is required to make, and also on the maximum closed loop resonance [1]. For civil aircraft flying qualities, it is usually the required pilot compensation, expressed in terms of amount of lead or lag which is the limiting factor, i.e. determines the handling qualities level.

The original Neal-Smith criterion was developed for fighter aircraft, and therefore the criterion was modified by Mooij at NLR [3]. Mooij derived modified boundaries, and made modifications to the pilot model to make the criterion more relevant to transport aircraft.

Different boundaries are available for different flight conditions. Neal-Smith is included in MIL-STD-1797A [4], and it is described in detail in reference [1].

2.2.2 Bandwidth and Phase Delay

Bandwidth is a criterion designed to determine that the pilot can achieve a satisfactory aircraft response at higher frequencies. The bandwidth may be calculated from the pitch response transfer functions, and then this value compared to the minimum permitted bandwidth according to the criterion.

The bandwidth is generally calculated for the pitch attitude and flight path transfer functions. This is then compared to limits for flying qualities levels. Minimum limits have traditionally been placed on bandwidth, but maximum limits are still quite new, being proposed by Field [5]. Bandwidth is contained within the MIL-STD-1797A flying qualities document [4].

Bandwidth may also be related with phase delay. Phase delay is related to the amount of time delay in a particular aircraft response parameter (such as pitch attitude), and limits are defined on phase delay, since an excessive time delay will cause the pilot problems, and even Pilot Induced Oscillation.

Bandwidth and Phase Delay are described in detail in reference [1].

2.2.3 Control Anticipation Parameter

Control Anticipation Parameter was initially developed as a measure of the predictability of flight path control [6]. It is designed to relate the initial pitch acceleration, which is what the pilot 'sees' through the pitch attitude response and 'feels' through the pitch attitude acceleration to the steady state normal acceleration, which is what the pilot 'feels' and which is also related to the final flight path response. CAP can also be shown to be proportional to the aircraft manoeuvre margin through its initial derivation, and this property is exploited in the derivation of the formula for calculating it.

CAP in its defined form is only relevant to conventional aircraft, although the principle behind it is likely to be valid for all rate-like response characteristics. This was demonstrated during the previous set of evaluations [1]. Therefore some modification is required before the criterion may be used with non-conventional response types and this is covered under the Generic Control Anticipation Parameter section, see section 2.2.4.

The detailed theory behind CAP is described in reference [1], and is included in MIL-STD-1797A [4].

2.2.4 Generic Control Anticipation Parameter (GCAP)

The proposed Generic Control Anticipation Parameter is an extension of the Control Anticipation Parameter. It is based on the Steady Manoeuvring Force and Pitch Sensitivity Criterion (SMFPSC) [3], which is a criterion that empirically calculates a value which is equivalent to the CAP value for conventional aircraft from their time responses, but may also be calculated for non-conventional response types.

This criterion is described in detail in reference [1]. The difference between this criterion and the SMFPSC is in the way in which the parameter is calculated. This criterion uses the full order aircraft response, while the SMFPSC is based around a constant speed approximation to the response characteristic in question.

2.2.5 Gibson's Dropback Criterion

The dropback criterion was initially developed by Gibson, and relates the way the pitch attitude response behaves when step inputs are made. It was subsequently modified by Mooij for transport aircraft, and has been successfully used in the previous series of evaluations [1]. It is described in detail in that document.

2.2.6 Gibson's Phase Rate Criterion

Phase rate was initially derived by Gibson, and is used as a measure of the way that the phase lag changes as the frequency increases. It is related to phase delay, and is generally used as a criterion for determination of Pilot Induced Oscillation (PIO) tendencies. It is described in detail in reference [1].

2.2.7 Gibson's Attitude Frequency Response Boundaries

Gibson also proposed boundaries for the pitch attitude frequency response. These are of the form of boundaries on a Nichols chart. These boundaries were proposed from the best configurations in the LAHOS and 'fighter flying qualities' experiment data [7, 8]. Separate boundaries were proposed for the up and away (figure 2.1), and the landing phase (figure 2.2).

For the landing phase, the boundaries were found to be best correlated by plotting them on a relative amplitude scale, with the 0dB point co-incident with the 120 degree phase lag for the landing approach phase, and at the 0.3 Hz frequency point for the up and away phase [6]. However, it must be remembered that these boundaries are for fighter aircraft. These results confirmed the usefulness of a K/s attitude response (i.e. a pitch rate demand system) at low frequencies, and a defined limits of how the response may depart from the ideal at higher limits.

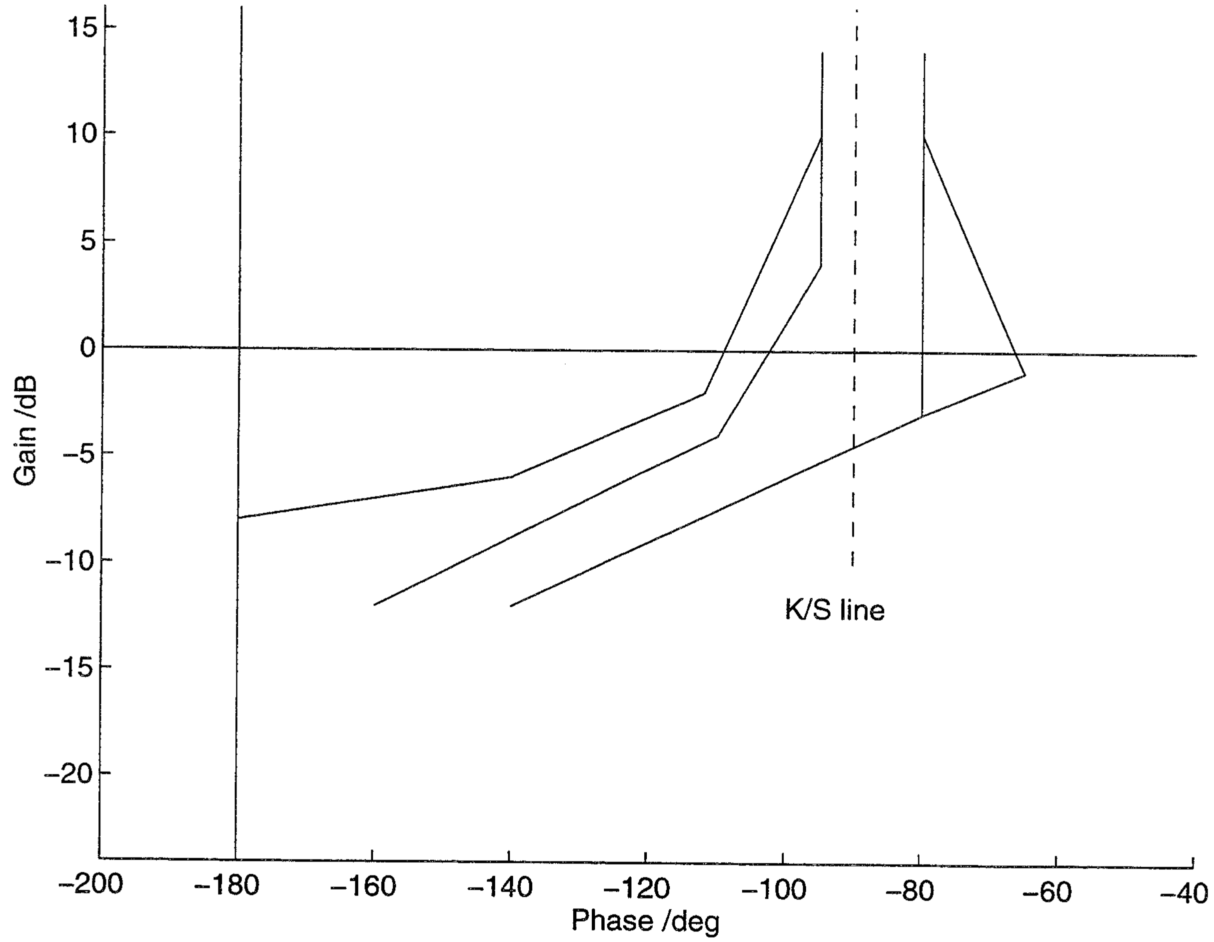


Figure 2.1: Gibson's Up-And-Away Frequency Response Boundaries

These boundaries were redefined further in later years, and have been widely used for pitch tracking design [6]. One utilisation has been with the McDonnell Douglas C-17 [9]. The up-and-away Gibson boundaries were used with the C-17 in the air-to-air refuelling task. The initial C-17 control laws were were found to be PIO prone in this flight phase, and therefore improvements were made based on Gibson's boundaries. This resulted in the aircraft having much improved flying qualities for this particular task.

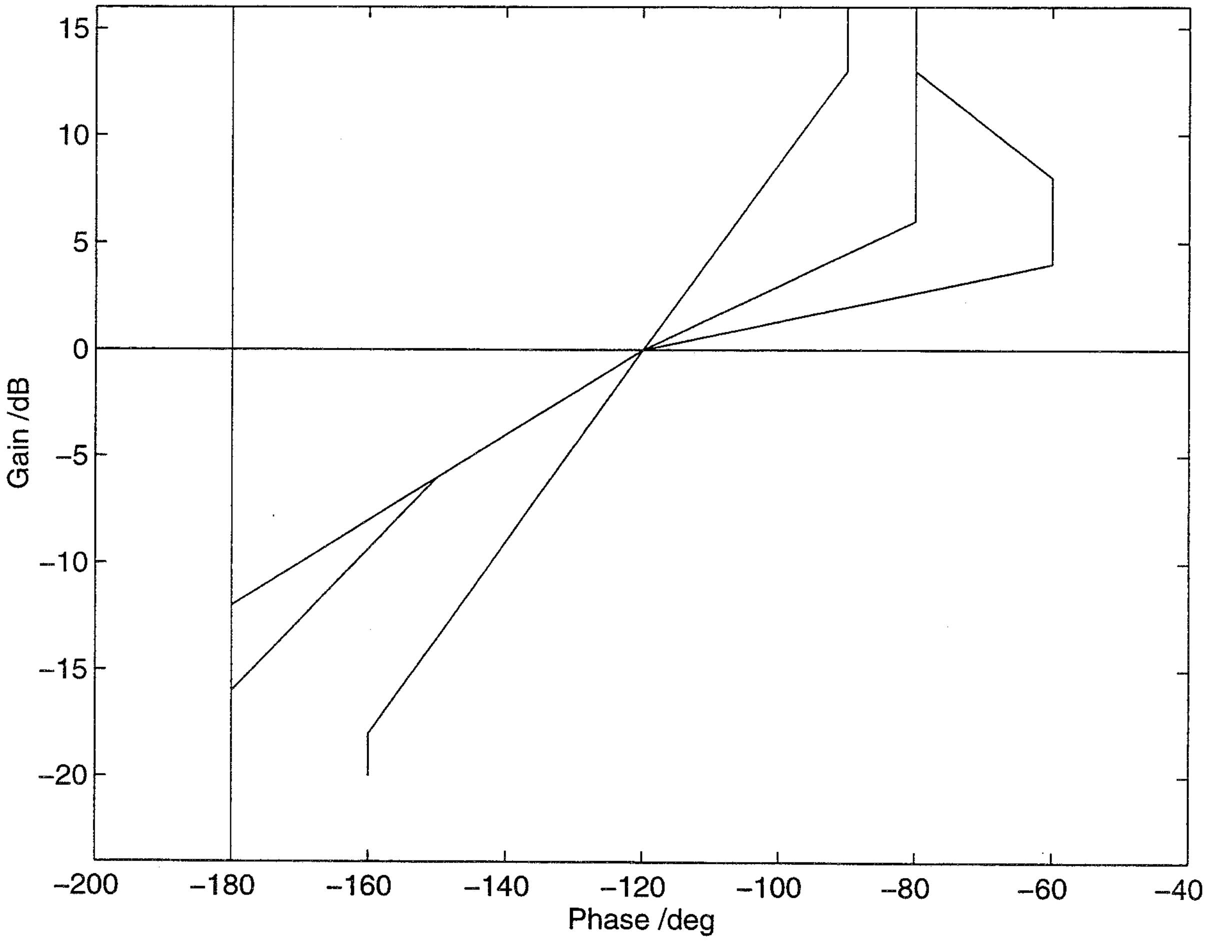


Figure 2.2: Gibson's Landing Frequency Response Boundaries

2.3 Workload Measurement

During the previous evaluation, workload measurements were taken. Two main scales were used; NASA TLX (Task Load Index) and the Bedford Workload scale. Although the NASA TLX scale has been successfully used in previous workload studies, it was found to be time consuming to complete for individual laws, and the results were not readily comparable between different pilots. Much more success was achieved with the Bedford scale. Its layout is familiar to the pilots since it is very much like the Cooper Harper Rating scale, and the pilots were generally happier in using it. The Bedford ratings from the previous set of trials were also directly comparable with pilot comments.

Therefore, only the Bedford scale was retained for these evaluations.

2.4 Handling and Flying Qualities Regulations

The contents of the three main handling qualities documents are briefly described within. These documents are MIL-STD-1797A [4], the main US DoD document for military aircraft, and JAR 25 and FAR 25, which are the European / US civil large aircraft requirements respectively.

2.4.1 DEF STAN 00-970

DEF STAN 00-970 [10] is the UK Defence Standard for military aircraft procurement. It contains a series of requirements concerning the design requirements for aircraft, although only the handling and flying qualities requirements are considered here. The flying qualities requirements include constraints on :

- The Control Anticipation Parameter (CAP) criterion is given for different aircraft classes and flight conditions.
- Limits are placed on the stick force per g.
- Limits are placed on the short and long term mode damping requirements.
- Trim characteristics.
- 'Suitability requirements', i.e. the response characteristic must be suitable to the task for which it is intended.

2.4.2 MIL-STD-1797A

MIL-STD-1797A is the US DoD Military Standard for handling and flying qualities of Military Aircraft. It contains many criteria, which include the following :

- Control Anticipation Parameter (CAP), in combination with Low Order Equivalent Systems (LOES). This takes the aircraft response transfer functions, and 'matches' them to an effective classical aircraft response. Limits are placed on the amount of mismatch. This is then used by the CAP criterion to determine if the (possibly non-conventional) response meets the CAP requirement.
- Limits are placed on the equivalent time delay for the configuration.
- Limits are placed on the $\omega_{sp}T_{\theta_2}$ requirement.
- Limits are placed on the short period mode damping ratio.
- Limits are placed on parameters of the pitch rate time response, such as pitch rate overshoot, and initial time delay.

- The product of the control force gradient in steady manoeuvring flight Fs/n and the maximum frequency response amplitude ratio of pitch acceleration to pitch control force $|\ddot{\theta}/Fs|_{max}$ shall not exceed published (CAP) limits.
- Limits are placed on the Bandwidth (flight path and pitch attitude) through the bandwidth criterion.
- A modified Neal-Smith criterion is considered, which looks at acceptable pilot compensation.
- Gibson's Criteria, which consider the nature of the time response, in terms of pitch attitude dropback and the nature of the initial pitch rate response.

2.4.3 JAR 25 and FAR 25

JAR 25 [11] and FAR 25 [12] contain the following criteria :

- A control forces criterion (25.143), limiting the maximum forces which may be applied in any axis.
- A static stability criteria (25.173), which places a requirement on the return to speed nature of the configuration.
- A short period damping criteria (25.181) which states that the mode must be heavily damped.

These are obviously very much more limited in their definition, and little detail is included with the criteria themselves.

The MIL-STD is by far the superior document, and the design criteria used within this program are contained within it. However, some of the requirements are currently too lax, and a revision is currently under production.

The JAR / FAR requirements are very much more limited, and are restricted solely to aircraft with classical response types, whereas the MIL-STD may be applied to both classical and non-classical response types.

Chapter 3

Control Law Design

The control laws from the previous study were designed to a series of law-independent criteria, which were then translated into actual designs. A multi-point design was used, taking account of both airspeed and configuration changes. The following design points were used.

1. 120 knots - flap 4
2. 140 knots - flap 3
3. 160 knots - flap 2
4. 180 knots - flap 1
5. 200 knots - flap 0
6. 220 knots - flap 0
7. 240 knots - flap 0
8. 260 knots - flap 0

Design Requirements

The following design requirements were used

- A GCAP value of 0.6 rad s^{-2}/g at 120 knots, with the value at higher airspeeds being maintained at about this value due to lack of better information.
- A pitch attitude dropback of 0.5 at an airspeed of 120 knots, decreasing to 0.4 at 140 knots etc, down to zero at airspeeds of 220 knots and above.
- A short term mode damping ratio of 0.7 for all flight cases.

- A speed stability level of 4 knots /lb for all flight cases for control laws where airspeed stability is required.
- A long term damping ratio of at least 0.1 for all flight cases
- An initial pitch acceleration of 0.6 deg s^{-2} /lb for all flight cases
- A non-monotonic flare characteristic.
- Stick re-datuming with trim for all flight cases.

These are intended as strict guidelines, but due to problems with designing complex control laws such as these, a slight error was tolerated on these parameters for the final control law designs. For example, the tolerance generally used on short term mode damping ratio was ± 0.01 since a pilot will not be able to distinguish damping ratios this accurately.

The major difference from the previous set of evaluations in the requirements and designs are listed below.

1. The speed stability level was decreased from the previous set of evaluations. This modification was made since problems were experienced with the long term mode damping at the higher static stability levels and higher airspeeds, and the results suggested that the amount of speed stability used may have been greater than the optimal.
2. The long term mode damping ratios were increased. The major effect of this was seen at higher speeds with the Nz and NzU laws.
3. Pitch attitude feedback was used. This increased the long term mode damping.
4. For the pitch rate demand law, the forces were increased in the flare to reflect the pilot comments from the previous evaluations. The forces in the flare with the speed feedback law were reduced to to the decreased speed error feedback gain.
5. The short term mode natural frequency was increased at constant values of dropback and GCAP.

The laws produced using this process were similar to the laws designed for the first set of evaluations, since the improvements were essentially incremental. The design process for the laws is documented in the report from the first evaluations [1].

Stick Datum

Stick datuming was added in the following way. For the unaugmented aircraft (law 0), and the augmented angle of attack (law 1), the existing feel system was retained. This datumed the control wheel in proportion to the horizontal stabiliser position.

For the positive speed stability control laws, the stick datum was moved as a function of the trimmed reference speed. The zero datum reference speed was 180 knots (i.e. with the stick datum in the mid-point), and a reference gradient of 30 knots/inch was used, i.e. a trimmed speed of 120 knots gave a datum position of 2 inches aft of the mid point.

For the angle of attack laws, the stick datum was moved as a function of trim reference angle of attack. The zero datum angle of attack was 2 degrees, and a subsequent gradient of 2 degrees per inch was used, i.e. a reference value of 8 degrees gave a stick datum position of 3 inches aft. This gave movements which were comparable to the trim system for the baseline aircraft, with a slightly greater movement.

For both of the speed and angle of attack datums given above, the datum position was limited to ± 3 inches.

3.1 Control Law analysis against the criteria

The control law characteristics can be seen in the following set of tables 3.1 to 3.11 and in figures 3.3 to 3.6.

Gibson's attitude frequency response boundaries

The response plots given for these control laws (figures 3.1 and 3.2) are plotted using a time delay of 20 ms, and the actuator is included in the response. The actuator is modelled as a first order lag with a 60 ms time constant.

It can be seen that the response plots for law 10 is more or less within the proposed boundaries. Laws 1, 3 and 7 are just outside, and laws 0 and 6 are well outside the desired region.

Bandwidth

The values for the pitch attitude and flight path bandwidths can be seen in tables 3.1, 3.2 and 3.3, and figures 3.3 and 3.4. It can be seen that all of the augmented configurations have level 1 bandwidth characteristics, but the unaugmented aircraft is borderline level 2 / 3.

Phase Delay

The phase delay characteristics can be seen on tables 3.1, 3.2 and 3.3 and figure 3.5. It can be seen that all of the configurations should not be PIO prone for the short term response characteristics.

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)
0	0.784	0.456	49.50	0.069	2.56
1	1.866	0.884	48.85	0.068	4.91
3	2.037	0.832	45.25	0.063	4.99
6	1.816	0.858	30.94	0.043	6.32
7	1.852	0.814	33.13	0.046	5.88
10	1.956	0.836	35.51	0.049	5.81

Table 3.1: Bandwidth and phase delays - 120 knots flap 4 gear down

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)
0	1.027	0.587	45.91	0.064	2.86
1	2.234	1.048	47.61	0.066	5.41
3	2.422	0.890	46.37	0.064	5.53
6	2.076	0.896	30.47	0.042	7.14
7	2.287	0.875	31.42	0.044	7.13
10	2.494	0.962	34.23	0.048	7.02

Table 3.2: Bandwidth and phase delays - 140 knots flap 4 gear down

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)
0	1.427	0.800	47.56	0.066	3.48
1	3.006	1.325	47.92	0.067	6.49
3	3.217	1.043	53.44	0.074	6.46
6	1.847	0.828	57.81	0.080	4.09
7	3.436	0.997	30.09	0.042	10.82
10	3.879	1.237	32.59	0.045	10.29

Table 3.3: Bandwidth and phase delays - 200 knots flap 0 gear up

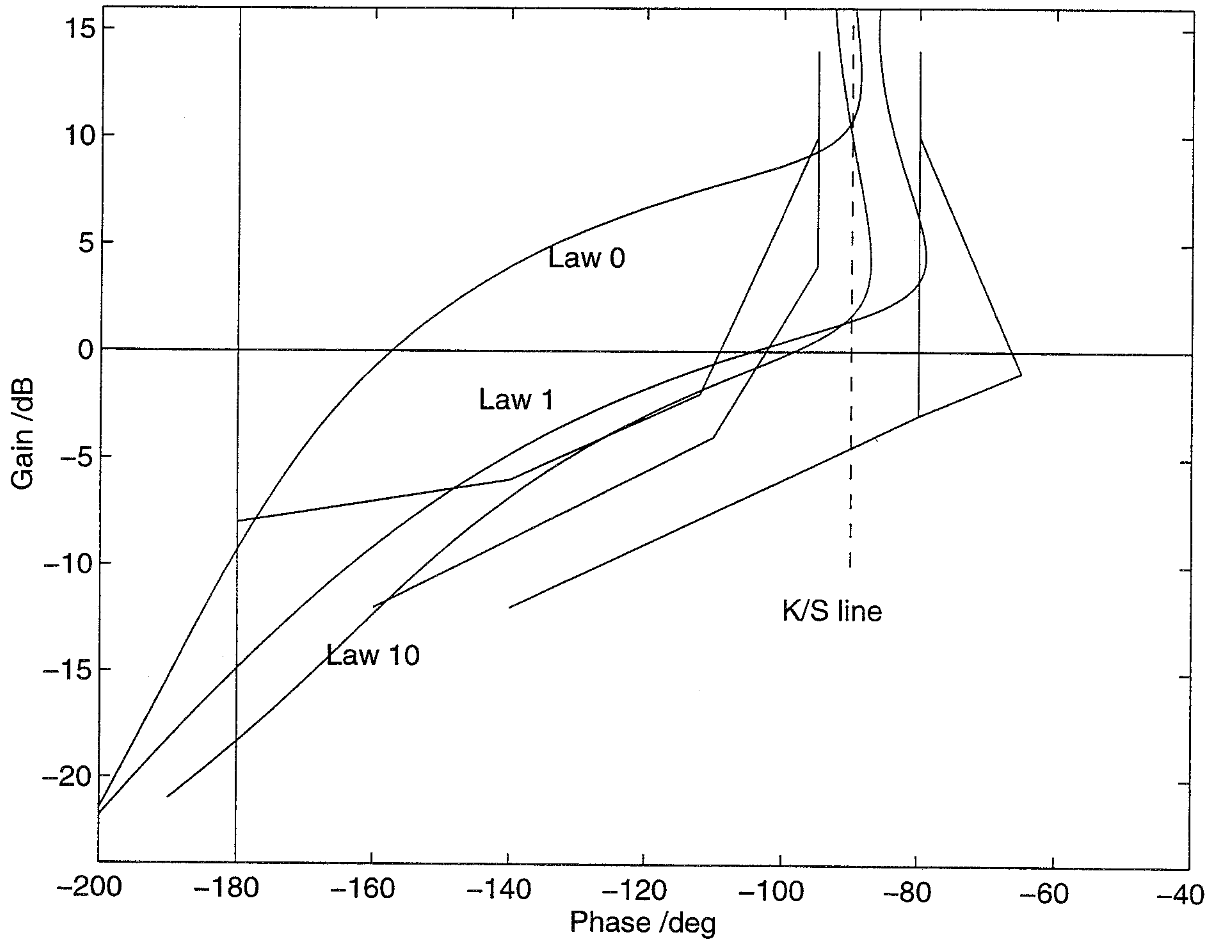


Figure 3.1: Gibson's Criterion - Laws 0, 1 and 10

Neal-Smith

The Neal-Smith characteristics can be seen in tables 3.6, 3.5 and 3.4, and on figure 3.6 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

From table 3.7 and 3.8, it can be seen that all of the augmented control laws have approximately similar values of GCAP, although the CAP values do not correspond to the GCAP values very well for some of the different control laws.

The difference between GCAP method 1 and GCAP method 2 is method 2 uses the maximum initial pitch acceleration, while method 1 uses the pitch acceleration after the first 0.1 seconds.

	200 knots, flap 0, with actuator		200 knots, flap 0, no actuator	
	NS compensation (deg)	NS resonance	NS compensation (deg)	NS resonance
0	17.3 lead	-1.81 dB	11.44 lead	-1.88 dB
1	21.68 lag	-3.00 dB	22.79 lag	-3.00 dB
3	13.32 lag	-3.00 dB	13.62 lag	-3.00 dB
6	4.83 lag	-2.96 dB	4.90 lead	-2.99 dB
7	11.32 lag	-3.00 dB	11.42 lag	-3.00 dB
10	17.87 lag	-3.00 dB	17.97 lag	-3.00 dB

Table 3.4: Neal-Smith compensation and resonance values for 200 knots flap 0

	140 knots, flap 4, with actuator		140 knots, flap 4, no actuator	
	NS compensation (deg)	NS resonance	NS compensation (deg)	NS resonance
0	72.31 lead	-2.94 dB	62.85 lead	-3.00 dB
1	12.38 lag	-2.72 dB	13.01 lag	-2.95 dB
3	8.882 lag	-3.00 dB	9.117 lag	-3.00 dB
6	3.949 lag	-2.38 dB	3.807 lag	-2.53 dB
7	5.379 lag	-3.00 dB	5.475 lag	-3.00 dB
10	10.46 lag	-3.00 dB	10.66 lag	-3.00 dB

Table 3.5: 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
0	114.4 lead	-3.00 dB	98.84 lead	-3.00 dB
1	2.275 lag	-2.07 dB	2.788 lag	-2.48 dB
3	2.618 lag	-2.88 dB	2.537 lag	-3.00 dB
6	0.968 lag	-1.29 dB	0.655 lag	-1.58 dB
7	2.276 lead	-2.53 dB	2.998 lead	-2.75 dB
10	1.234 lag	-2.57 dB	1.064 lag	-2.79 dB

Table 3.6: Neal-Smith compensation and resonance values for 120 knots flap 4

	200 knots, flap 0			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
0	0.196	0.191	0.099	0.210	0.208	0.107	0.188	0.187	0.096
1	0.664	0.520	0.289	0.691	0.612	0.331	0.665	0.604	0.323
3	0.997	0.435	0.249	1.000	0.558	0.309	0.965	0.595	0.325
6	0.411	0.196	0.118	0.448	0.526	0.308	0.453	0.588	0.335
7	0.810	0.496	0.331	0.748	0.566	0.334	0.690	0.573	0.326
10	0.929	0.599	0.391	0.846	0.630	0.368	0.757	0.600	0.338

Table 3.7: CAP and GCAP values with and without the elevator actuator (act) method 1

	200 knots, flap 0			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
0	0.196	0.197	0.172	0.210	0.212	0.191	0.188	0.190	0.174
1	0.664	0.586	0.454	0.691	0.666	0.541	0.665	0.648	0.538
3	0.997	0.489	0.401	1.000	0.609	0.512	0.965	0.639	0.548
6	0.411	0.208	0.212	0.448	0.620	0.478	0.453	0.674	0.529
7	0.810	0.679	0.477	0.748	0.667	0.518	0.690	0.647	0.524
10	0.929	0.806	0.566	0.846	0.738	0.571	0.757	0.673	0.544

Table 3.8: CAP and GCAP values with and without the elevator actuator (act) method 2

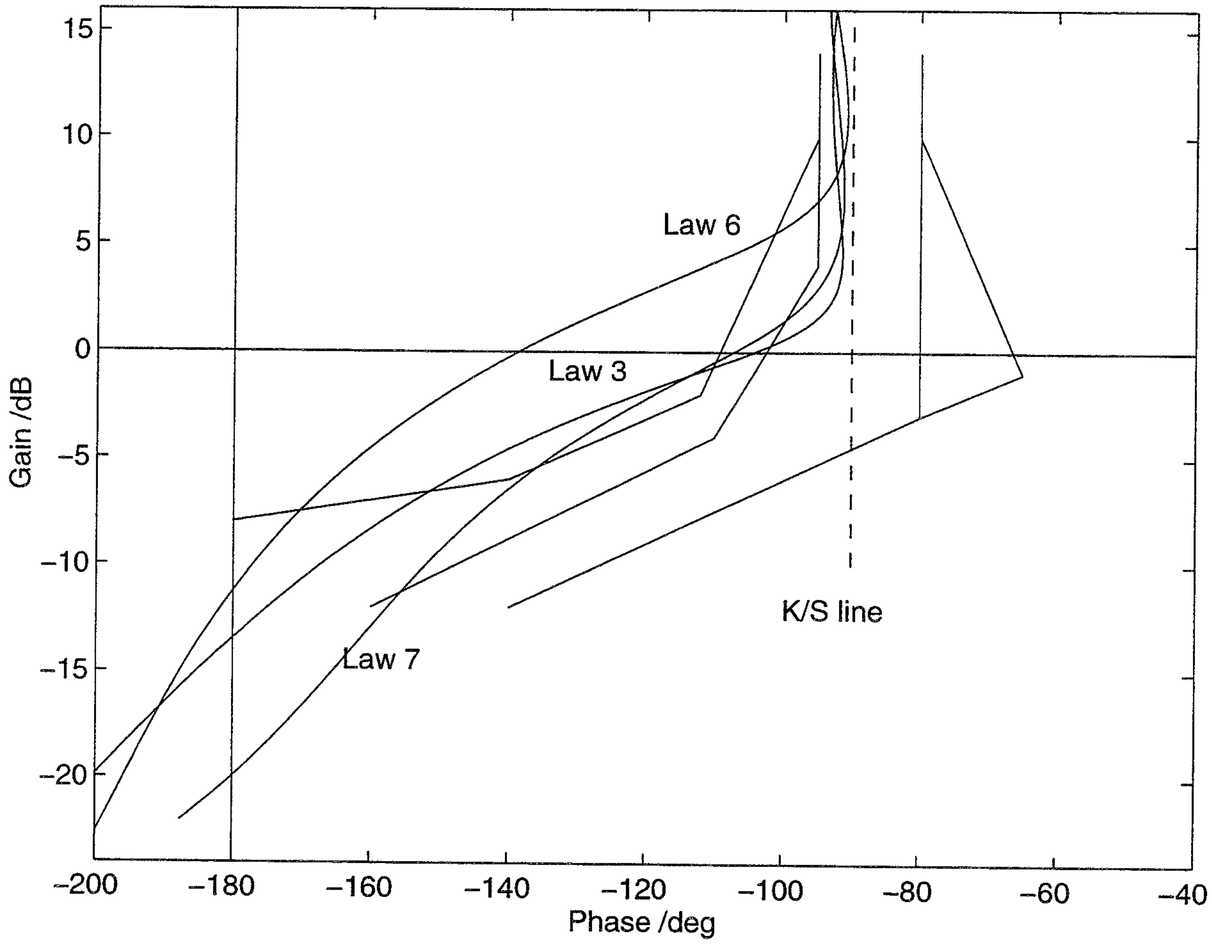


Figure 3.2: Gibson's Criterion - Laws 3, 6 and 7

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 baseline 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 3.9, 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.

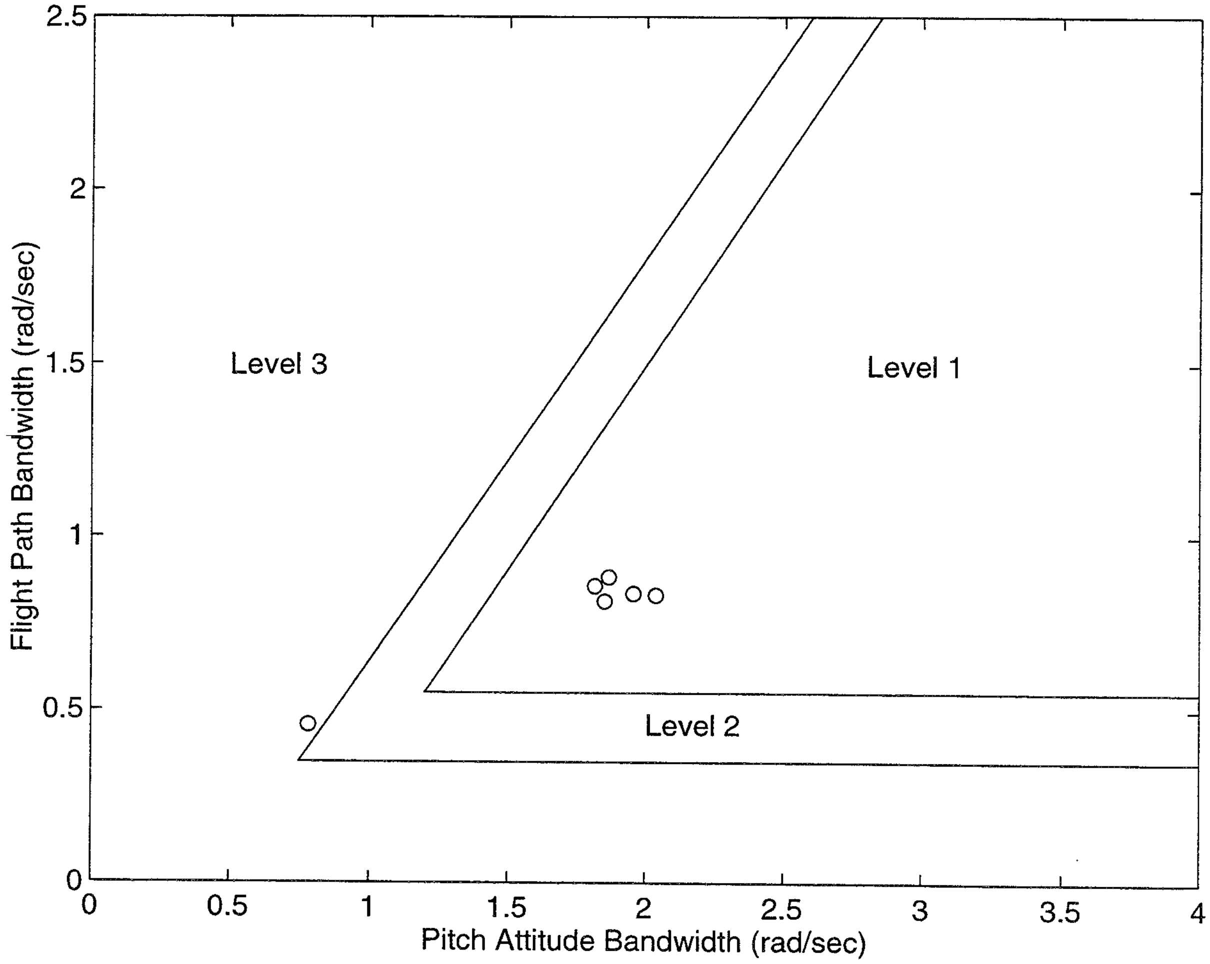


Figure 3.3: Pitch attitude bandwidth versus flight path bandwidth for the landing flight case (120 knots, flap 4)

Long Term Mode Characteristics

From table 3.10, 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 3.11, 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

	200 knots, flap 0		140 knots, flap 4		120 knots, flap 4	
	ω_{st} (rad s^{-1})	ζ_{st}	ω_{st} (rad s^{-1})	ζ_{st}	ω_{st} (rad s^{-1})	ζ_{st}
0	1.31	0.54	0.94	0.55	0.75	0.61
1	0.71	2.41	1.71	0.69	1.40	0.70
3	2.95	0.68	2.05	0.70	1.69	0.69
6	1.89	0.71	1.37	0.73	1.16	0.71
7	2.66	0.70	1.77	0.71	1.43	0.69
10	2.85	0.69	1.89	0.70	1.50	0.69

Table 3.9: Longitudinal short term mode characteristics

	200 knots, flap 0			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)
0	0.08	0.29	78.8	0.09	0.14	68.3	0.15	0.05	41.5
1	0.09	0.24	67.4	0.15	0.20	42.4	0.17	0.16	37.3
3	0.11	0.21	55.7	0.13	0.27	47.2	0.14	0.33	43.6
7	0.10	0.18	62.1	0.12	0.16	52.8	0.13	0.17	49.8
10	0.09	0.22	68.7	0.11	0.15	54.8	0.13	0.13	49.9

Table 3.10: Longitudinal long term mode characteristics

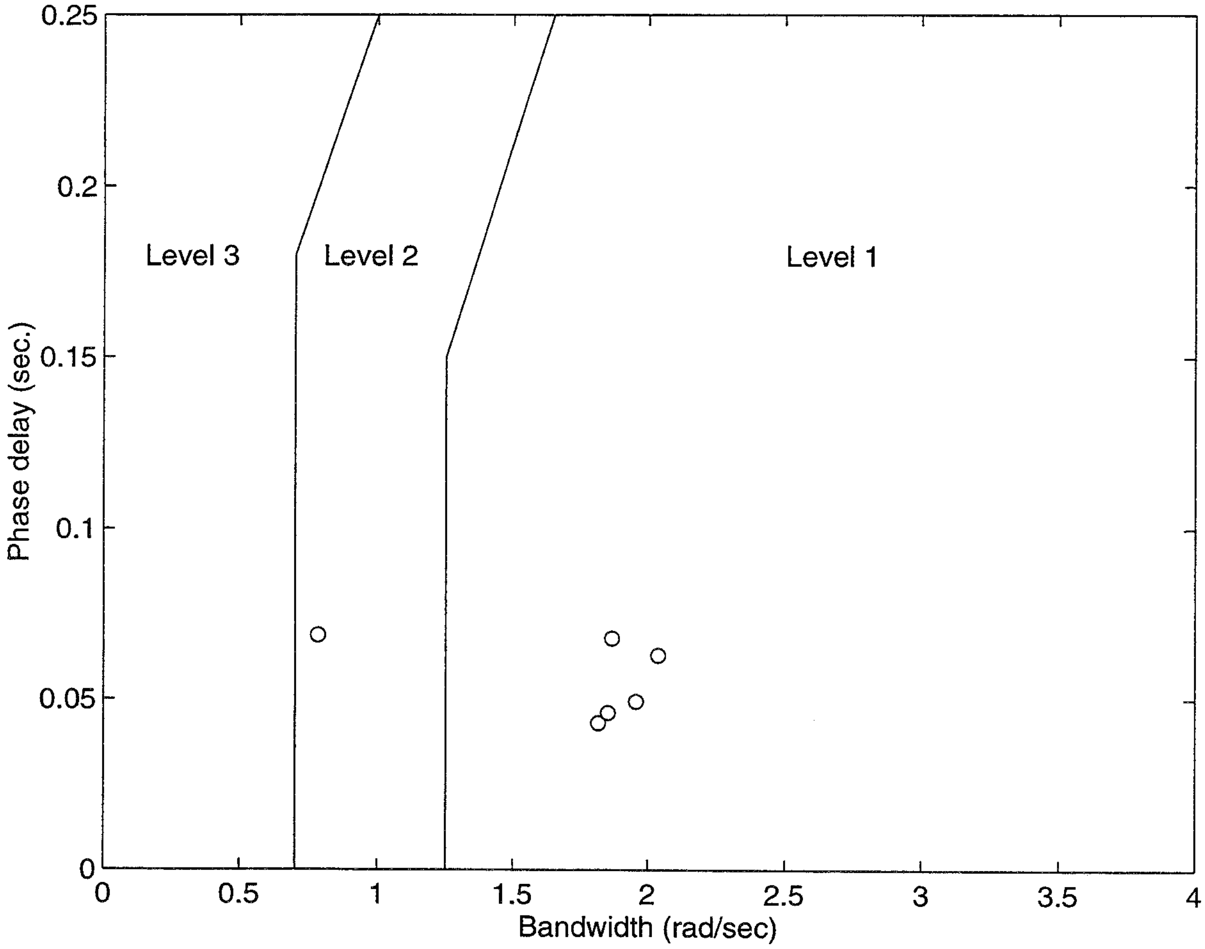


Figure 3.4: Pitch attitude bandwidth versus phase delay for the landing flight case (120 knots, flap 4)

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.

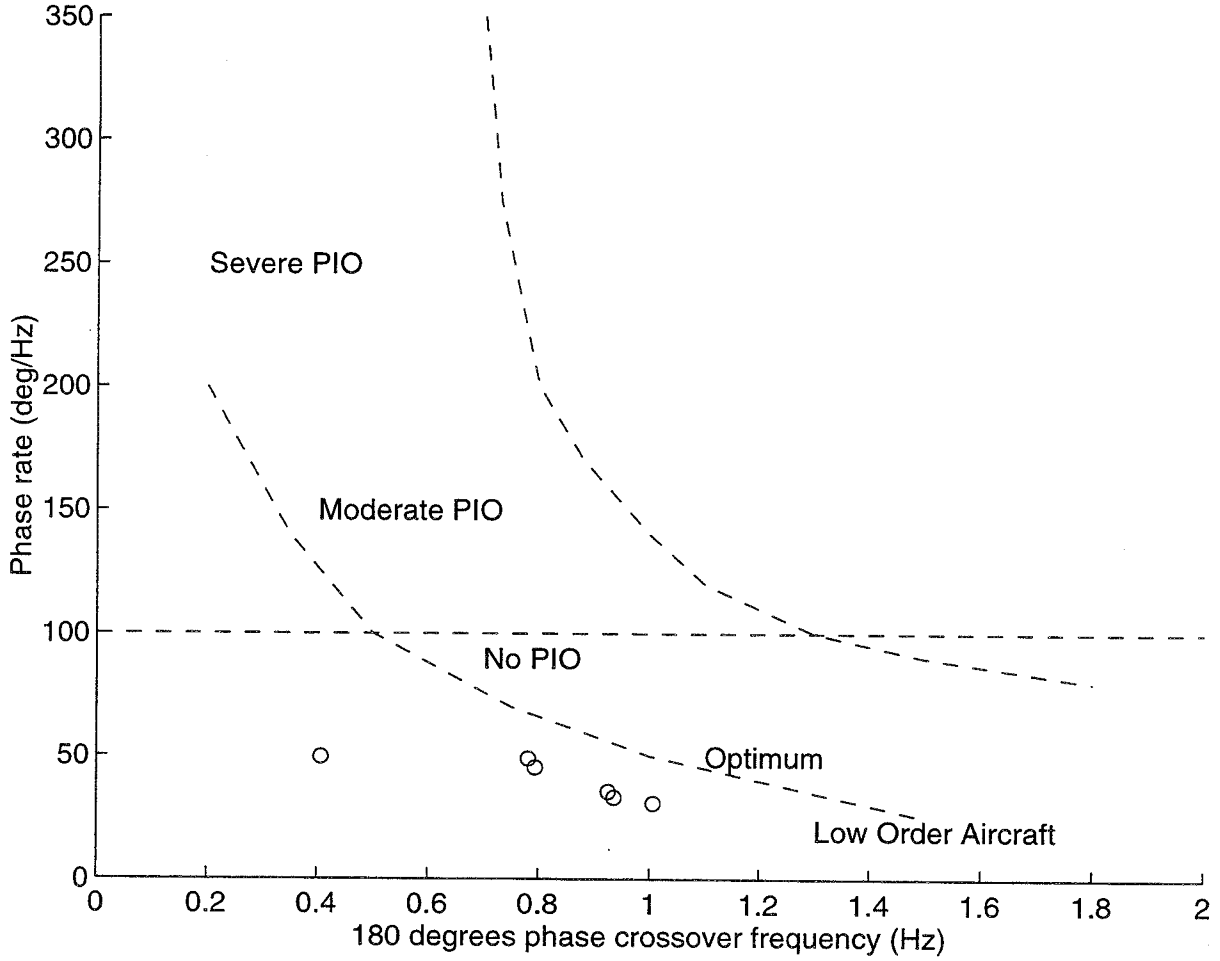


Figure 3.5: Phase rate versus phase crossover frequency for the landing flight case (120 knots, flap 4)

	$\frac{d\gamma_{MAX}}{d\theta_{SS}}$	ω_{BW_θ} (rad s^{-1})	$\omega_{BW_{\gamma P}}$ (rad s^{-1})	$\omega_{BW_{\gamma CG}}$ (rad s^{-1})
0	1.52	0.784	0.456	0.421
1	1.44	1.866	0.884	0.740
3	0.96	2.037	0.832	0.664
6	0.63	2.168	1.363	0.766
7	1.07	1.852	0.814	0.679
10	1.11	1.956	0.836	0.680

Table 3.11: Hoh's Flare Criterion Parameters, 120 knots, flap 4

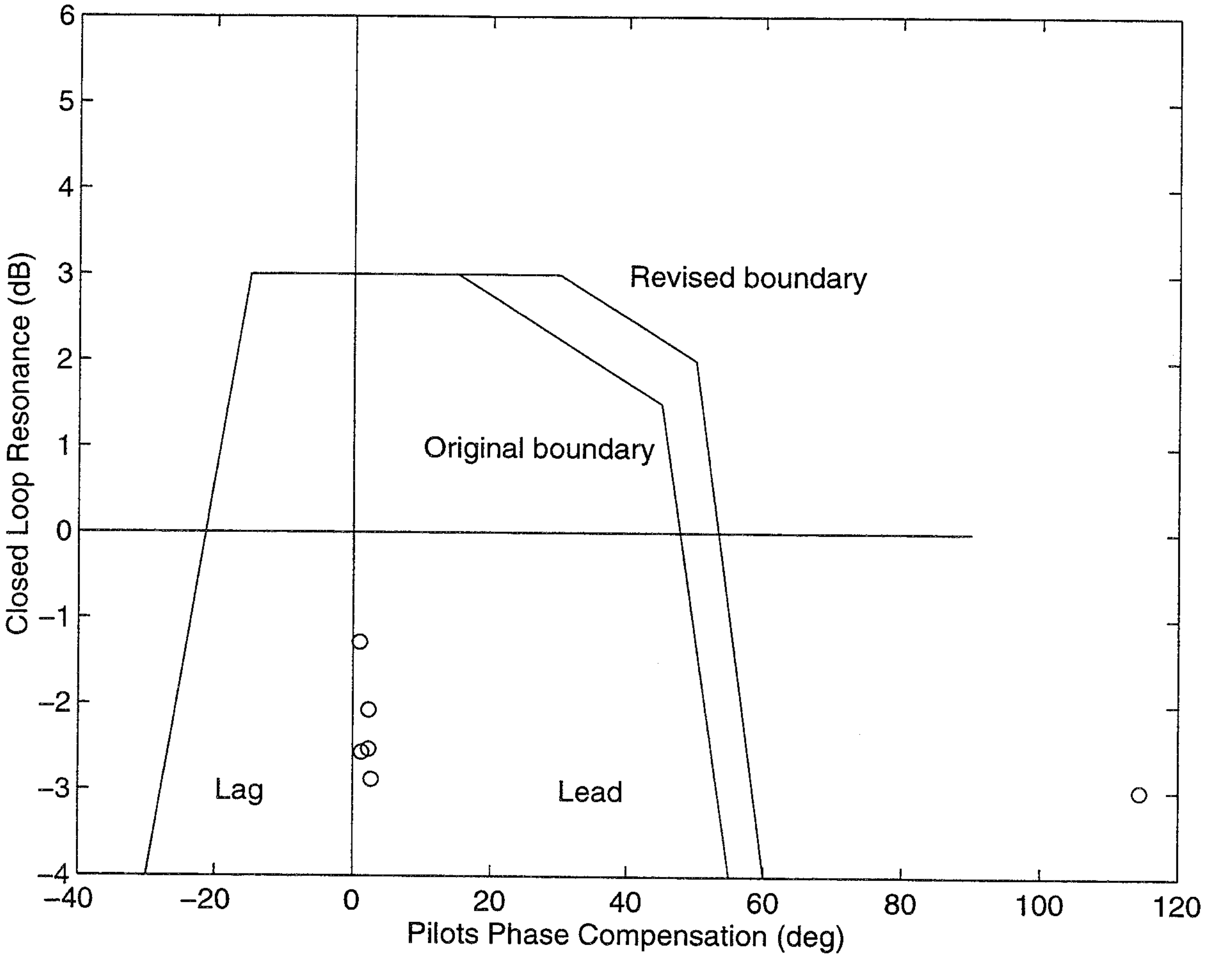


Figure 3.6: Neal-Smith Characteristics for the landing flight case (120 knots, flap 4)

Chapter 4

Aircraft Description

4.1 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.

4.2 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.

4.3 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.1.

4.4 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 [13].

4.5 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.

4.6 Engine Model

Four engine levers are fitted, but only the inner two are used since the aircraft under consideration is a twin-engined aircraft. 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.

4.7 Atmospheric Disturbances

Atmospheric disturbances were available in the model. For the approach and landing evaluation, windshear was used. For the formation flying task, neither windshear or turbulence were used.

4.8 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. Positions 4 was used for the approach and landing task, and position 0 for the formation flying task.

4.9 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 which was modelled in the engineering simulator.

The control laws designed here have considered speeds up to 260 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 5

Experiment Design

This chapter describes the evaluation procedure used for the handling qualities experiment. De-Witt [14] states that the tests must meet four definite criteria.

1. Instantaneously measurable performance
2. Operationally relevant
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. A tight formation flying task
3. ILS tracking performance
4. The effects of windshear

5.1 Approach Task

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

1. Start at 3 miles and 140 knots ($V_{REF} + \approx 20$ knots) configuration 4, and at 1150 feet on the QNH (900 feet above aerodrome level). The aircraft is therefore fully established on the Instrument Landing System (ILS). The aircraft was flown along the ILS in this configuration, and the pilot was briefed to slow the aircraft down to 121 ($V_{REF} + 5$ knots) by 300 feet AAL.
2. At 300 feet, the pilot was briefed that there would be a decreasing headwind shear, the headwind at 300 feet being 30 knots, while the headwind below 50 feet AAL was 0 knots. The pilot was asked to maintain the glideslope and airspeed during this segment.
3. The final part of the task was to flare and land within the marked touchdown zone.

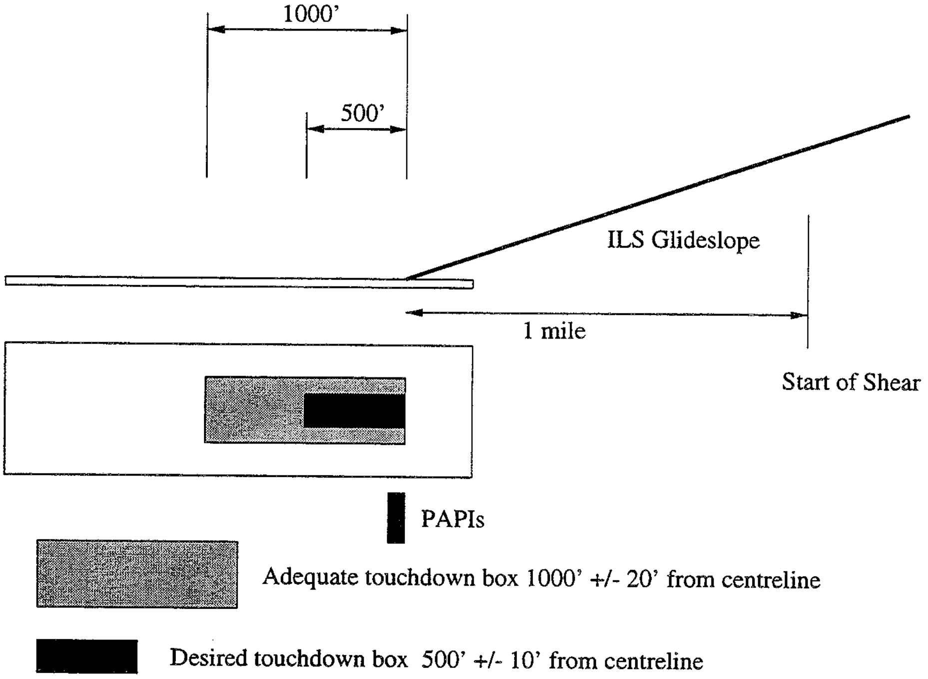


Figure 5.1: Approach evaluation procedure used

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, and then the pilot and test administrator completed the pilot comment card.

5.2 Formation task

The evaluation task used comprised the following segments :

1. Start at approximately 1180 feet behind the aircraft on which the formation task is to be performed, 250 feet below, and at the same airspeed and heading. The view behind the receiver aircraft can be seen on figure 5.2.

2. Accelerate to climb and close the distance behind the aircraft. The distance at which the formation lights illuminate can be seen on figure 5.3, and the colour code for the lights can be seen on figure 5.4.
3. Maintain the position for a period of at least two minutes from when the receiver was first stabilised within the limits previously defined.

The tanker was programmed to be a silhouette, which was dark in colour (against the slightly lighter sky), but was effectively translucent. A box of lights (described in the next paragraph) was mounted on the tail of the tanker (on the aircraft centreline), and there was also a line of lights running from the tail to the nose of the tanker. Finally, there was a tail light (actually at the centre of the box) and two wingtip lights mounted on the tanker which were used for formating on the tanker. These lights were visible above the distance at which the other lights started to illuminate (nominally 1180 feet), and gave the pilot sufficient cues as to the orientation and position of the tanker.

The arrangement of lights requires some explanation. It was designed to give the pilot a measure of both his position in relation to the centreline of the tanker, the distance from the tanker (including the distance from the ideal position), and also a measure of the rate of closure in relation to the tanker. The lights were arranged so that when the pilot was closer than the distance at which the light illuminated, the light would be on.

The pilot was briefed with the following desired and adequate performance bounds. The total task duration was 2 minutes. For the lateral and vertical task, the pilot was briefed that if the aircraft centreline lights remained within the box for more than 90 seconds, then the performance was desired, if the centreline lights remained within the box for 30 to 90 seconds, the performance was adequate, and if the centreline lights were in the box for less than 30 seconds the performance was less than adequate. A similar set of timings were used for the distance task, except that the desired distance was defined as being between 75 and 105 feet behind the tanker, i.e. with any number of the amber lights illuminated, all of the white lights illuminated, and none of the red lights illuminated.

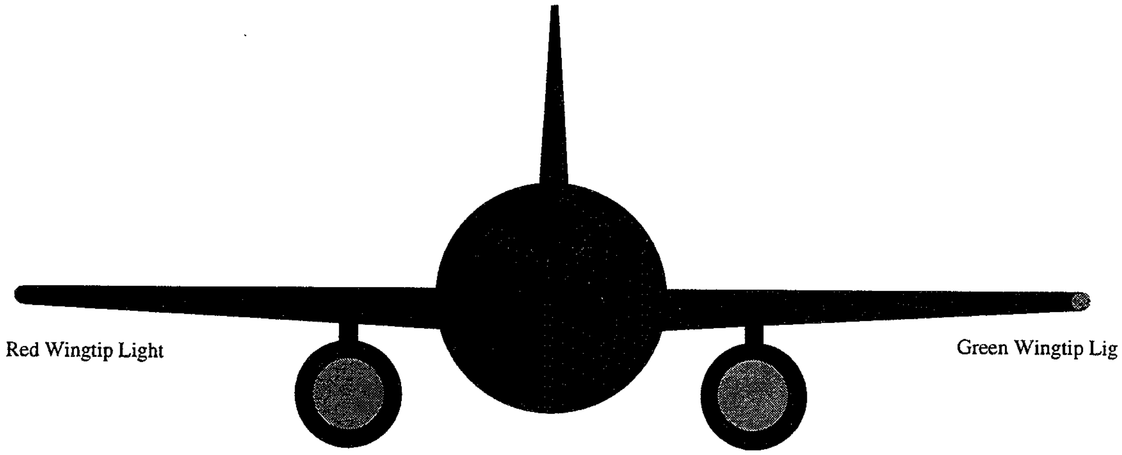
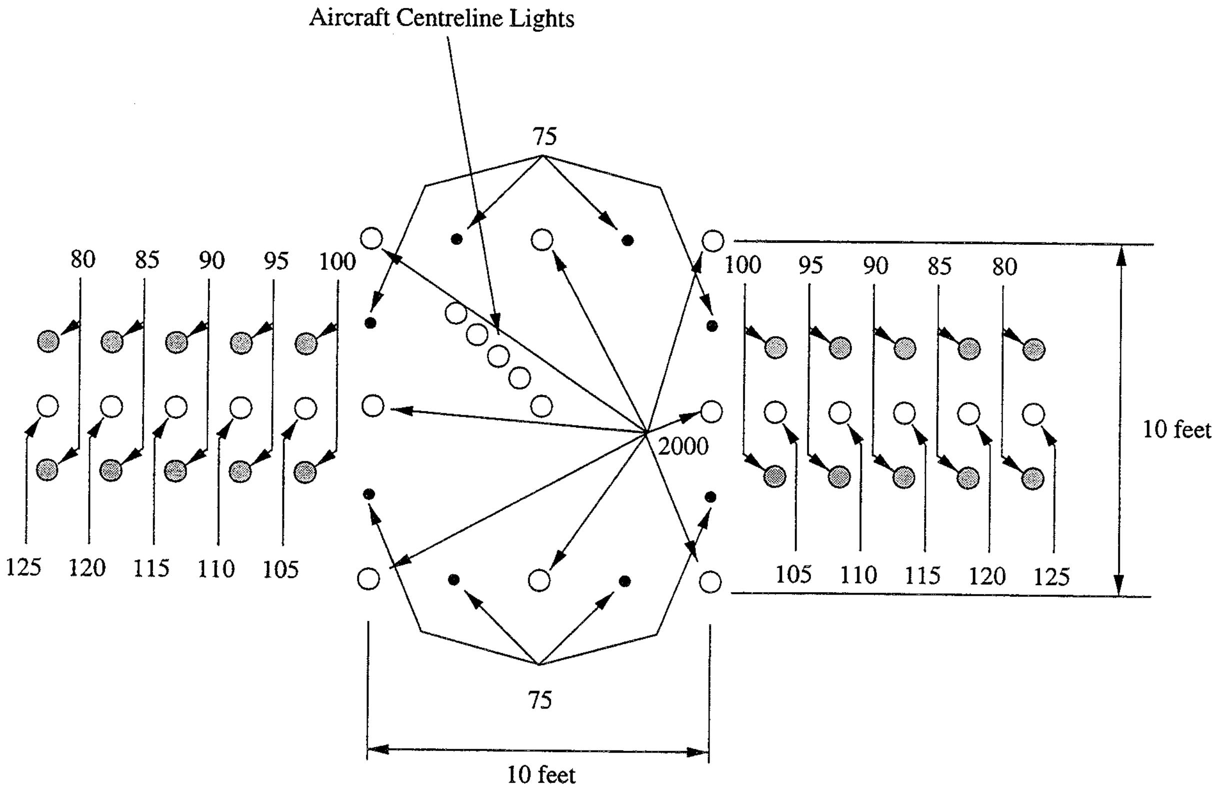


Figure 5.2: View from the Receiver Aircraft



The numbers represent the distance at which the light is visible to the pilot
The length of the aircraft centreline lights is 115 feet

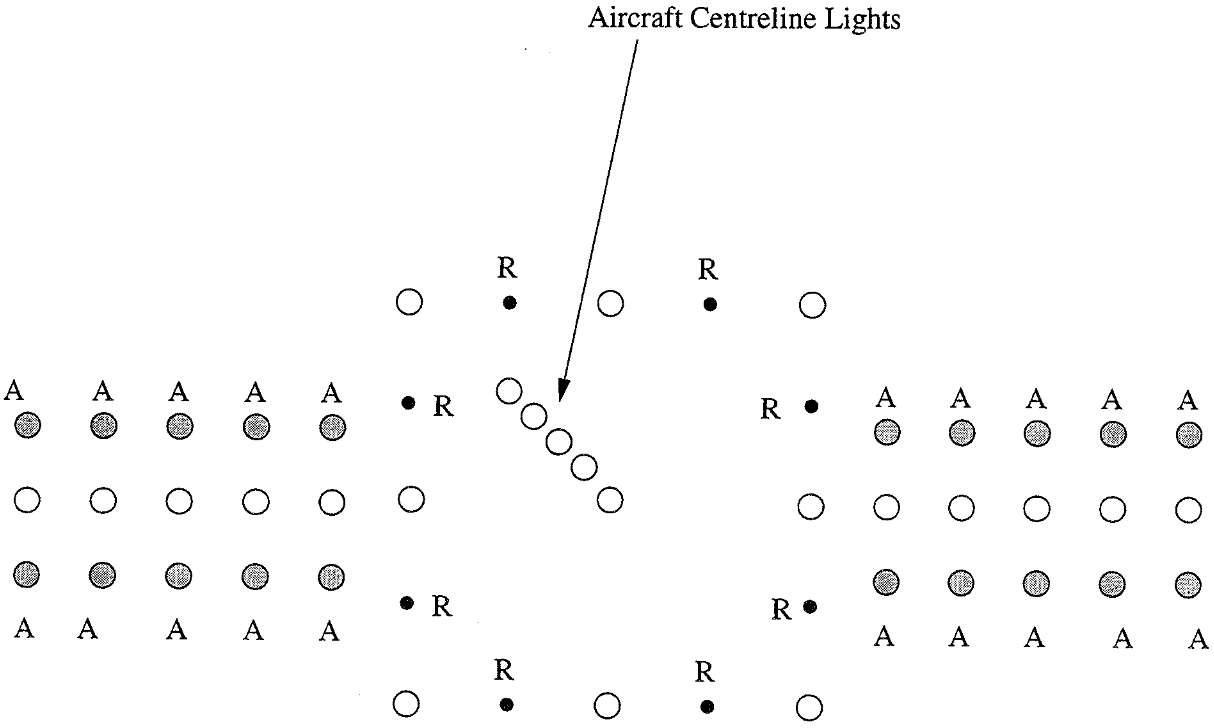
Figure 5.3: Distance at which the formation lights illuminate

This evaluation segment was flown once. The evaluation pilot was initially given a practice approach with the unaugmented (baseline) aircraft to familiarise himself with the procedure. After the task, the pilot and test administrator completed the pilot comment card.

5.3 Rating scales

In addition to completing pilot comment cards, the following rating scales were used.

- The Cooper Harper Rating Scale was used for flying qualities assessment.
- The Bedford Workload Scale was used for workload assessment.
- The Pilot Induced Oscillation Scale was used to give a measure of any pilot induced oscillation problems.
- The Cranfield Handling Qualities Rating Scale was used as a trial. It has a similar format to Cooper Harper, but is a multi-dimensional scale. Cooper Harper ratings are taken in the



Colour Code for the lights :

White	No code
Red	R
Amber	A

Figure 5.4: Colour code for formation lights

longitudinal, lateral and directional axes. In addition, the ability to trim and the ability to control the airspeed are assessed. A weighting for each rating is then used to obtain an overall rating. For more information, see reference [15].

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

Two pilots took part in these evaluations. The first is a former RAF Test Pilot with previous handling qualities and large aircraft experience, and the second is an experienced civil flying instructor, with some, although limited 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 E - Gary Giles

He has accumulated nearly 1400 hours, much of it instructing on light aircraft. In addition, he has flown a number of twin aircraft. He is a BX rated CAA examiner, and is authorised to carry out flight tests. He now flies Slingsby Fireflies for Hunting Aviation at RAF Barkston Heath.

Pilot	Configurations	Evaluations	Approaches
A	6	13	15
E	6	12	16
Total	12	25	31

Table 6.1: Evaluation Summary

6.2 Approach Summary

In total, 2 pilots made 31 approaches during at total of 2 evaluations with 11 different control law configurations, plus a number of approaches to a simulated tanker aircraft. Both pilots 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-3	16th January 1997.
E-1	18th February 1997.

In addition, a calibration session was carried out by the author in January 1997 to check the simulator performance, and that the control laws were performing as designed. No modifications were made after that session. 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.

6.2.1 Cooper Harper Ratings

The Cooper Harper ratings can be found in tables 6.2 to 6.5 for the approach and landing task.

6.2.2 Approach segment Cranfield Handling Qualities Rating

The Cranfield Handling Qualities Rating scale results for the approach segment of the windshear task can be found in table 6.6.

6.2.3 Bedford Workload Ratings

The Bedford workload ratings can be found in table 6.2.3 for the approach segment.

Law	Pilot A	Pilot E	Median
0	4	3	3.5
1	4	3	3.5
3	3	2	2.5
6	2	2	2
7	2	2	2
10	3	2	2.5

Table 6.2: Approach Cooper Harper Ratings

Law	Pilot A	Pilot E	Median
0	5	6	5.5
1	5	6	5.5
3	5	5	5
6	3	3	3
7	4	4	4
10	4	3	3.5

Table 6.3: Shear Cooper Harper Ratings

Law	Pilot A
0	6
1	3
3	3
6	3
7	5
10	3

Table 6.4: Flare Cooper Harper Ratings

Law	Pilot A
0	5
1	4
3	4
6	3
7	4
10	3

Table 6.5: Overall Cooper Harper Ratings

Law	Long Char	Lat Char	Dir Char	Trim	Speed	CFDHQR
Weighting	4	4	3	3	4	
0	5	2	2	2	3	2.89
1	3	2	2	2	3	2.44
3	3.5	2	2	2.5	3	2.64
6	1	2	2	2	2	1.78
7	3	2	2	1	2	2.06
10	2	2	2	2	2	2.00

Table 6.6: Approach Cranfield Flying Qualities Rating Scale

Law	Pilot A
0	3
1	4
3	3
6	2
7	2
10	3

Table 6.7: Approach Bedford Workload Rating

6.2.4 PIO Ratings

The overall PIO ratings for the approach segment of the windshear task can be found in table 6.2.4.

6.2.5 Touchdown Data

The touchdown data for the approach and landing task can be found in table 6.9.

Law	Pilot A
0	3 (app), 4 (flr)
1	1
3	1
6	1
7	1
10	1

Table 6.8: Pilot Induced Oscillation Rating

Pilot	Eval No.	Law	V_{50}	H_{50}	V_{td}	H_{td}	X_{td}	Y_{td}
A	35	10	119.7	11.2	113.9	3.9	278	4.3
A	35	10	119.6	8.1	116.5	5.9	34	-1.8
A	36	3	120.6	11.4	117.0	4.6	411	14.1
A	36	3	114.2	8.2	115.6	5.6	-131	0.7
A	36	3	118.3	8.0	113.9	4.7	-68	5.8
A	37	1	117.2	12.6	113.7	2.7	-72	4.3
A	37	1	116.1	13.6	114.3	3.9	-66	7.9
A	37	1	119.4	11.2	114.9	5.0	-52	2.5
A	38	6	116.5	7.3	113.2	7.1	-122	1.2
A	38	6	119.9	11.3	113.7	2.8	400	-0.8
A	39	7	118.5	14.4	111.0	4.8	347	-2.7
A	39	7	119.4	11.8	113.0	4.8	107	8.1
A	40	0	119.0	12.6	112.3	3.7	184	7.5
A	40	0	120.0	11.6	114.5	4.5	-160	0.6
A	40	0	120.6	10.7	118.0	3.1	-192	1.8
E	41	6	112.7	17.9	108.2	4.3	-614	-3.3
E	41	6	109.2	7.3	109.9	5.2	-164	-0.8
E	41	6	120.2	22.5	118.6	8.8	-194	13.4
E	41	6	104.5	20.5	109.3	8.6	-1538	1.0
E	42	7	126.8	15.2	118.9	2.0	945	0.1
E	42	7	123.5	12.6	115.8	4.1	223	4.3
E	42	7	109.7	19.4	108.4	11.4	-1117	17.4
E	42	0	108.2	23.5	112.4	10.0	-793	9.5
E	43	10	122.1	5.5	118.2	2.9	313	12.3
E	43	10	124.3	9.1	118.9	4.1	263	3.5
E	43	7	110.9	22.9	109.5	12.1	-415	19.2
E	44	3	124.4	14.7	120.7	0.2	253	9.0
E	44	3	123.4	12.2	122.3	4.2	260	1.7
E	45	1	112.4	23.2	113.2	15.7	-436	3.4
E	45	1	120.8	9.3	119.5	3.2	0	-3.6
E	46	0	120.5	15.8	120.6	3.1	-298	9.4

Table 6.9: Touchdown performance data

Law	Pilot A
0	4
1	4
3	3
6	5,5
7	3
10	4

Table 6.10: Formation Cooper Harper Ratings

Law	Long Char	Lat Char	Dir Char	Trim	Speed	CFDHQR
Weighting	4	4	3	3	4	
0	5	4	2	3	4	3.72
1	4	3	2	2	4	3.11
3	3	3	2	2	4	2.89
6	5	3	2	2	5	3.56
6	5	3	2	2	5	3.56
7	2	3	2	2	3	2.44
10	4	3	2	2	3	2.89

Table 6.11: Formation Cranfield Flying Qualities Rating Scale

6.3 Formation Task Results

This section contains the results from the formation flying task.

6.3.1 Cooper Harper Ratings

This section contains the Cooper Harper ratings for the formation flying task (see table 6.10).

6.3.2 Formation Cranfield Handling Qualities Rating

This section contains the Cranfield Handling Qualities Rating scale for the formation flying task can be found in table 6.11.

6.3.3 Bedford Workload Ratings

The Bedford workload ratings can be found in table 6.3.3 for the formation task.

Law	Pilot A
0	6
1	5
3	4
6	6,6
7	3
10	4

Table 6.12: Formation Bedford Workload Rating

Law	Pilot A
0	4
1	2
3	2
6	3,3
7	1
10	2

Table 6.13: Pilot Induced Oscillation Rating

6.3.4 PIO Ratings

The overall PIO ratings for the formation task can be found in table 6.3.4.

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. Each task is also discussed independently.

7.1 Approach Task

As a result of the previous evaluations, some initial control law 'filtering' had already been carried out to remove control law types which would not be appropriate. As a result of this, the remaining laws were known to be suitable for the approach task. Therefore the effects of windshear were to be assessed for these known laws.

7.1.1 Response Characteristics

No problems were experienced with the response characteristics in terms of abruptness or sluggishness. Using the 'Constant CAP' design approach, the initial responses of all of the laws was neither abrupt or sluggish. This confirms the results of the previous evaluations, especially since most of the laws were redesigned, resulting in a 'short term mode frequency extension' capability, i.e. the laws all had a constant CAP value, but an increased short term mode natural frequency. In addition, all of the laws were designed to specified dropback values (either positive or zero), which was another contributory factor. Laws with overshoot (i.e. negative dropback) have been found to be slightly sluggish [3].

Furthermore, none of the augmented configurations had a problem with the flight path / pitch attitude consonance, suggesting good flight path dynamics and a suitable CAP / dropback combination. As previously shown [1], increasing the dropback has a tendency to reduce the flight path delay.

7.1.2 Trim Characteristics

The trim characteristics were generally found to be desirable. One pilot liked the positive movement of the control wheel with trimming at low speed for the normal acceleration with trim to angle of attack law. However, comments may have indicated that this law may have had too much wheel movement, resulting in quite a far aft position at low speeds. This requires further investigation. Additional pilot comments also indicated that wheel datum movement may only be desirable at low speed, and the rear control wheel position indicates that the pilot is at a low airspeed. Again, this requires further investigation.

7.1.3 The effect of Windshear

The windshear penetration gave some interesting results. The control law which gave the best ratings for the windshear penetration was the normal acceleration law with no static stability. This was due to the fact that the aircraft did not have a tendency to pitch as the airspeed changed, and therefore the pilot had more time for airspeed control. If an autothrottle had been fitted, the difference to the speed stable laws may not have been quite so large since the autothrottle would reduce the airspeed transients. The normal acceleration control law received the best ratings from the majority of the pilots when flown during the previous set of evaluations, due to the maintenance of flight path during an airspeed change. It has been said that trimming can improve the airspeed awareness, but although these evaluations have shown through pilot comments that there is a benefit present, the magnitude of the benefit may be surprisingly small.

7.1.4 Control Forces

The control forces were considered appropriate for all of the laws tried. Again, all of the laws were designed to a constant value of GCAP and a constant initial pitch acceleration per unit wheel force. This gave effectively a constant stick force per g value for each law, of approximately 60 lb/g at approach airspeeds. The initial pitch acceleration was kept constant as the airspeed increased, and therefore the stick force per g changed as the GCAP value changed with airspeed. No unfavourable comments were received concerning the stick forces at the higher airspeeds tested, and at the airspeeds used for the formation flying task, the stick force per g would still be around 60 lb/g.

7.1.5 Flare Characteristics

Some modifications were made to the flare law from the results of the previous programme. For the pure normal acceleration law, the stick force required to maintain a constant pitch attitude in the flare was increased from 60 to 100 lb/rad. In other words, the pilot was required to hold a force of 100 lbs to maintain a pitch attitude of 1 radian greater than that of the reference attitude [1]. This gave much more desirable characteristics, as comments from the previous evaluations indicated that the stick forces were a little light. The comments obtained for the modified flare law used for these evaluations included 'surprisingly conventional'.

However, for the speed stable laws, the effective forces in the flare were reduced due to the fact that the stick force required to hold an off-trim airspeed was reduced (from around 3 knots/lb to 4 knots/lb). Therefore, the forces in the flare were lighter. Pilot comment indicates that heavier forces are more desirable, and therefore for these trim to speed laws, an additional flare law would be required to increase the forces in the flare, if the desirably low levels of stick force per knot are used.

For law 10 (normal acceleration with trim to angle of attack), the control forces were deemed to be appropriate in the flare. Finally, for the augmented aircraft law, where the control wheel is still connected directly to the elevator, the control forces were also deemed to be appropriate.

7.1.6 Displays

A flight path vector display was used with the evaluations. Due to hardware limitations, the flight director bars were programmed so that they crossed the artificial horizon pitch attitude ladder at the effective flight path angle. The pilots found that they were very useful, and despite the implementation, which sometimes lead to the pilot interpreting the bars as an actual flight director, the pilot's found that they were using them more and more. However, comments like 'I'm using it more and more, and it's disappointing me' were found, and further investigation revealed that the display warranted improvement though some form of quickening / prediction.

The speed trend vector display was found to be useful, and as with previous evaluations [5, 1], it made the airspeed tape display workable, and assisted with the airspeed control task through giving the pilot predicted information.

7.1.7 Lateral / Directional Control Laws

For the approach and landing task, the lateral / directional control laws were not a factor. This is unsurprising since they had been tried and tested previously, and were found to be suitable. In addition, the task was specifically designed so that only the longitudinal dynamics would be excited.

7.2 Formation Task

The formation task gave some interesting results. It turned out to be a tight flight path control task, with (unsurprisingly) very little head down time.

7.2.1 Longitudinal Control

With the formation task, a suitable GCAP value was not available. Therefore a number of different values were tried with each law. The target short term mode natural frequency was selected for each law based on experience, and also an attempt to maintain constant control law gain values. The choice of short term mode natural frequency was the only characteristic was the only design parameter which wasn't known - the laws were designed to a series of design parameters similar to those for the approach task.

The two laws which received the best rating were those where the law met Gibson's criterion (see section 2.2.7). In addition, these two laws had the greatest GCAP values. However, one law which was not rated so well had a GCAP value comparable with the value from these laws. Therefore it would seem that GCAP may be a factor, but Gibson's criterion almost certainly is a criterion. This would require further investigation to confirm, but designing a law which meets Gibson's criterion, and also has a reasonably high GCAP value (around 0.5 compared to the value of approximately 0.6 used for the approach) should produce a reasonable control law.

7.2.2 Lateral / Directional Control Laws

The same lateral control law was used for each of the individual longitudinal control laws, and therefore should have been a constant factor in the evaluations. Looking at the Cranfield Handling Qualities Rating scale for the formation task 6.11 showed that all of the directional ratings were 2, and all of the lateral ratings were 3, with the exception of law 0 (the unaugmented aircraft), which had a lateral rating of 4. This was probably due to the excessive workload experienced in the longitudinal task with the unaugmented aircraft, and hence resulting in a deterioration in the lateral control task. These ratings may be considered to be identical to Cooper Harper ratings for the purpose of this report.

7.2.3 Airspeed Control

Comments from the previous evaluations indicated that the gearing between the throttle position and engine response was too high, meaning that the pilot could not control the thrust as precisely as with some engines. This therefore gave some problems in the formation task. The solution was to use the airbrake. This was modelled as a pure drag brake, i.e. there was no pitching moment.

7.2.4 Stick forces

No comments were made concerning the wheel forces. However, the task was not aggressive enough to excite any large pitch forces. The pilot was briefed to acquire the tanker as quickly as possible, which required an increase in airspeed, and a climb, and no adverse comments were received concerning wheel force during this phase. All of the control laws were designed to have a constant initial pitch acceleration per unit stick force across the whole of the airspeed range, and this chosen value was the same for each individual law.

7.2.5 Trimming

The trim was only really used with the unaugmented configuration, and to a very limited extent, the augmented aircraft law. Both of these are laws where the control wheel is connected directly to the elevators. None of the augmented configurations warranted trimming, which is understandable since the task is flown at a reasonably constant speed.

7.3 Comparison against the Criteria

The configurations considered were compared to the criteria previously considered. The best control laws met all of the criterion proposed. However, some initial sorting of the criterion which have been proposed was initially performed to determine which were relevant.

It was generally found that most of the limits placed on the criterion were too lax, compared to the results of these evaluations. Gibson's criterion are the exception to this - they seem to have sufficiently tight boundaries that they can be used for design purposes. This is also true for the CAP criterion. Other criterion, such as the Bandwidth criterion and Neal-Smith seem to have quite relaxed boundaries, and therefore cannot be used specifically as design criteria. However, poor performance results if the control laws do not meet these boundaries, and therefore they are useful as a check that the proposed law is within limits.

The results confirmed the findings of the previous set of evaluations [1].

7.4 General Comments

These comments are intended to tie together the results from the two tasks considered here with the results from the previous set of experiments.

7.4.1 Longitudinal Response Characteristics

It was found that for the approach task, the GCAP criterion could be used to effectively design the short term dynamics of the aircraft. By using a constant GCAP value, no problems were found with the control laws in terms of abruptness or sluggishness, which would indicate that the characteristics of the short term mode is suitable. In addition, it was found that this GCAP value could be disconnected from the short term mode natural frequency so that improvements in short term mode natural frequency could be obtained but with still an 'optimum' GCAP value. It is also necessary to control the dropback values for the pitch attitude response since they also contribute to the pilot's impression of the control laws.

Therefore, the results of the first two sets of approach tasks indicate that in classical terms, the pilot is sensitive to manoeuvre margin, and this makes a suitable design parameter. The pilot is sensitive to static margin, but only due to the fact that he can tell if there is static stability or no static stability. Configurations with zero static stability do not seem to be penalised by this as long as the short term response (i.e. effective manoeuvre margin) is appropriate.

A constant initial pitch acceleration per unit stick force across the flight envelope / speed range seems to give acceptable control forces across the envelope, though this is probably also dependent on the effective GCAP value. Interestingly, analysis of an existing q-pot system tends to give a constant value of the initial pitch acceleration per unit stick force.

7.4.2 Trimming

From the previous evaluations, pilot comments indicated that trimming was desirable from a speed awareness point-of-view for the approach and landing task. However, for the windshear approach, the best performance was obtained from the non-speed stable law, since the law did not pitch down in response to the airspeed change. For the pre-windshear segment of the approach, the non-speed stable normal acceleration law and the trim to speed normal acceleration law received the best Cooper Harper Ratings from both pilots. This was due to the flight path angle hold characteristics of the laws combined with the trim to speed characteristic of law 7.

However, comments from the previous evaluations indicate that a pure normal acceleration law gives better performance when flown with an autothrottle, since the airspeed is 'dialled-in' on the autothrottle control panel, and a non-speed stable law will not require any subsequent pilot trimming action as the airspeed changes. Most of the pilots from the last evaluations liked this feature.

Therefore, this work so far has shown that an aircraft can be designed with trim to airspeed or trim to angle of attack control laws, but this static stability is not necessary for good flying and handling qualities. Comments from the non-test pilot, from this set of evaluations indicated that trimming does not necessarily improve a pilot's airspeed awareness, and is a task which requires some pilot attention that could more usefully be implemented in other ways. In addition, trimming becomes a subconscious act, and if the pilot is therefore removing any out-of-trim forces, he may not be consciously aware if he is off the trim speed, or he may not even be aware of what the trim airspeed is. This remarks are important since it is this type of pilot who will be flying and operating this aircraft on a daily basis.

In addition, autothrottles are becoming more and more widely used in general line operations - the Airbus A320 is rarely flown without the autothrottle engaged. If a non-speed stable law is optimal for an aircraft flown in autothrottle, then this should be implemented. From the previous evaluations, the best rating was for a pure normal acceleration law flown with autothrottle engaged. This rating came from an experienced military and civil test pilot, who had flown a wide variety of different laws, and had participated in a number of display and control law trials. His comments indicated the pure normal acceleration / autothrottle combination was almost perfect, and the configuration only lacked a flight path vector display.

7.4.3 Displays

As the evaluations series has progressed, more of the evaluation pilots have asked for a flight path vector. This type of display is useful since it shows the parameter that the pilot is trying to control, especially for an ILS approach. One evaluation pilot, who is also an Airbus A320 line pilot, used the vertical speed indicator in lieu of the flight path vector used on the A320. However, as mentioned before, this type of display suffers since it is necessary to filter the information used to generate the flight path angle as turbulence and other effects can have quite a severe effect. This filtering has the effect of adding lag into the system, which the pilot sees as a time delay. This can have a major effect on the flying qualities, and too great a delay may even make the display a hinderence.

The speed trend vector proved to be useful throughout the evaluations. With the airspeed tape display, it was used in lieu of the trend indications from a conventional airspeed indicator. This was also seen with the previous programme [5], where a similar effect was observed.

Some pilots remarked on the usefulness of a Head Up Display, both during some evaluations, and also in the subsequent debriefing. It was thought that a simple HUD would be useful for the task, as the essential information would be available in a readily accessible format. A limited information display would be useful, containing (for the approach task), a runway display with a flight path marker, an artificial horizon, and a fast/slow speed indicator. This would keep the pilot's eyes focused where they should be (outside the cockpit), and give him his essential information.

Chapter 8

Conclusions and Recommendations

This chapter contains the conclusions and recommendations.

8.1 Conclusions

- Good pitch dynamics give the pilot more time for airspeed control.
- For the windshear penetration task, the 'pure' normal acceleration law gives the best performance.
- The pilot is sensitive (in classical terms) to manoeuvre margin, and not to static margin, although he is aware of the presence of static margin.
- For the formation task, no benefit was found from having to trim to airspeed or angle of attack.
- The benefit of trimming for the approach and landing task to improve airspeed awareness is questionable, especially with the benefits found with non speed stable laws during windshear.

8.2 Recommendations

- Quickening of the Flight Path Vector display is required.
- More work to confirm the benefit of trimming in airspeed control is required.
- More work to look at the desirability of wheel re-datuming with speed / trim is required.
- More work is required for the formation task to assess the suitability of the proposed GCAP values and Gibson's criterion.

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