Supersonic transport aircraft longitudinal flight control law design

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ABSTRACT

Modern civil transport aircraft utilise increasingly complex command and stability augmentation systems to restore stability, optimise aerodynamic performance and provide the pilot with the optimum handling qualities. Provided it has sufficient control power a second generation fly-by-wire supersonic transport aircraft should be capable of exhibiting similarly desirable low-speed handling qualities. However, successful flight control law design requires identification of the ideal command response type for a particular phase of flight, a set of valid handling quality design criteria and piloted simulation evaluation tasks and metrics. A non-linear mathematical model of the European supersonic transport aircraft has been synthesized on the final approach to land. Specific handling quality design criteria have been proposed to enable the non-linear dynamic inversion flight control laws to be designed, with piloted simulation used for validation. A pitch rate command system, with dynamics matched to the aircraft's flight path response, will consistently provide Level 1 handling qualities. Nevertheless, pre-filtering the pilot's input to provide a second order pitch rate response, using the author's suggested revised constraints on the control anticipation parameter will generate the best handling qualities during the terminal phase of flight. The resulting pre-filter can be easily applied to non-linear dynamic inversion inner loop controllers and has simple and flight proven sensor requirements.

NOMENCLATURE

g	acceleration due to gravity
k	transfer function gain
I_{yy}	pitch moment of inertia
M_h	pitch moment effectiveness
$N(s)$	transfer function numerator term
n_α	normal load factor per angle of attack
n_z	normal acceleration
q_{pk}	peak pitch rate
q_{ss}	steady state pitch rate
$\dot{q}_d$	pitch acceleration demand
$\dot{q}_d$	pitch acceleration sensed
s	laplace operator
$1/T_{\theta 1}$	slow pitch zero
$1/T_{\theta 1}$	fast pitch zero (defining incidence lag)
U_e	axial component of equilibrium velocity
α	angle-of-attack
γ	flight path angle
η	elevator input
θ	pitch attitude
τ	time constant
ω_q	pitch rate bandwidth
ω_s	short period frequency
ζ	short period damping ratio

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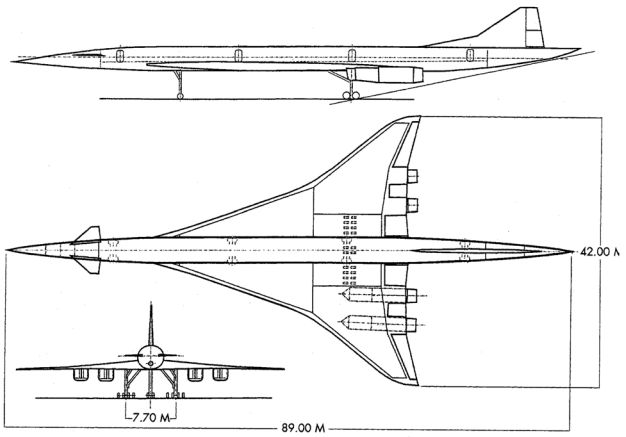


Figure 1. ESCT baseline with optional foreplane.

Abbreviations

AoA	angle-of-attack
CAP	control anticipation parameter
CHR	cooper-Harper rating
CSAS	command and stability augmentation system
DB	(pitch attitude) dropback
DoF	degree of freedom
EFIS	electronic flight instrumentation system
ESCT	European supersonic commercial transport
ESRP	European supersonic research programme
FBW	fly-by-wire
FCS	flight control system
GCAP	generic CAP
HDD	head down display
HQ	handling qualities
IAS	indicated airspeed
ICR	instantaneous centre of rotation
ILS	Instrument landing system
LCD	liquid crystal display
MLW	maximum landing weight
MP	manoeuvre point
MTOW	maximum take-off weight
MVC	multi-variable control
NDI	non-linear dynamic inversion
nm	nautical mile
OS	(pitch attitude) overshoot
PAPI	precision approach path indicator
PFD	primary flight display
PIO	pilot induced oscillation
SPPO	short period pitching oscillation
SST	supersonic transport

1.0 INTRODUCTION

The research presented within this paper was conducted by the author whilst employed within the control and simulation group of the Defence Evaluation and Research Agency (DERA) located at Bedford, UK. It forms part of a part-time PhD entitled 'Flight Control for Advanced Supersonic Transport Aircraft Handling Quality Design' completed in November 2001 at Cranfield University[1].

The work is also related to the larger European supersonic research programme (ESRP) carried out in collaboration with Airbus UK who, together with their Airbus industrial partners and respective research organisations, have been developing some of the key technologies that may enhance the viability of producing an environmentally and economically acceptable second-generation supersonic transport (SST) aircraft. A baseline configuration, known as the European supersonic commercial transport (ESCT), has been defined for use within the studies, Fig. 1.

For the purposes of the flight control study, ESCT consists of three elevon control surfaces located inboard, mid)and outboard of the engine exhaust nozzles on the trailing edge of the port and starboard wings. The control surfaces are currently configured to operate as single port and starboard units which move symmetrically as elevators to provide pitch control, and asymmetrically as ailerons, to provide roll control. The conventional fin mounted rudder provides yaw control in the usual way. The foreplane has not been used for this study.

1.1 Technical background

It is acknowledged that Concorde's unique low-speed handling qualities are acceptable when flown in a rigidly procedural manner by experienced pilots[2,3]. However, to be commercially viable and environmentally acceptable, more numerous ESCT aircraft would need to provide increased passenger carrying capacity, range and the flexibility to integrate with existing large civil transport aircraft during the terminal phase of flight. ESCT's much larger size, weight and inertia compared to Concorde's, combined with the use of increasing levels of relaxed longitudinal stability to improve aerodynamic efficiency, may result in unconventional dynamics and associated degraded handling qualities in the terminal phase of flight, where precise manual flight path control is required.

Modern large civil transport aircraft are equipped with full authority fly-by-wire (FBW) flight control systems (FCS) which enable the utilisation of increasing levels of relaxed longitudinal stability to minimise trim drag, reduce control surface size and hence improve overall aerodynamic efficiency. The FCS can restore stability margins and provide alternative pilot command type functions, defined by the command and stability augmentation system (CSAS), suited to the aircraft type and current task[4]. Hence, FBW equipped aircraft inevitably possess handling qualities, which are no longer a natural function of the aircraft aerodynamics because of the strong influence of the CSAS design. An additional advantage is the ability to provide common-handling characteristics across an airline's fleet, providing the possibility of reduced aircrew conversion training, reduced workload, automatic detection systems and hence increased operational safety.

1.2 Handling qualities

Handling qualities have been defined by Mooji *et al*[5] as "those characteristics which will have a major influence on the safety and mission effectiveness (guidance and control precision) of the pilot-vehicle system". This is supported by Cook[6] who states that "The flying and handling qualities of an aeroplane are those properties which describe the ease and effectiveness with which it responds to pilot commands in the execution of some flight task." Cook goes on to distinguish between the flying and handling qualities as "the flying qualities may be regarded as task related, whereas the handling qualities may be regarded as being response related". Mooji goes on to split handling qualities into criteria and requirements. Handling quality (HQ) criteria are defined as design guidelines for use by control system designers and authorities, whereas the customer requirements for airworthiness have to be demonstrated to the certification authorities as having been met and may be supported by the criteria.

Since the development of Concorde[2], considerable advances have been made into what constitutes desirable handling qualities and how these can be quantified. SST specific HQ criteria and guidelines were formulated during the 1960s to early 1980s, within both the US and European SST research and development programmes[7-10]. The resulting HQ criteria were developed for conventional aircraft by assuming classical characteristics with minimal flight control augmentation.

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Generic HQ research has been ongoing in Europe and the USA both within industry and academic communities. Fortunately, most of the generally accepted HQ criteria (and some more contentious) are contained within the US Department of Defense Interface Standard Flying Qualities of Piloted Aircraft (MIL-STD-1797A)[11]. This substantial document contains many HQ criteria and supporting metrics that have been shown to be applicable to both classical and non-classical high-order systems and response types. These are referenced to:

I Classes of aircraft (based on size, weight and manoeuvrability):

- Class I – small light aeroplanes.
- Class II – medium weight, low to medium manoeuvrability aeroplanes.
- Class III – large, heavy, low to medium manoeuvrability aeroplanes.
- Class IV – high manoeuvrability aeroplanes.

Hence ESCT, with a 340 tonnes maximum take-off weight (MTOW) and 174 tonnes maximum landing weight (MLW), is classified as Class III.

II Flight phase categories, which are divided into:

- Category A – non-terminal involving rapid manoeuvring, precision tracking or flightpath control such as flight refuelling.
- Category B – non-terminal involving gradual manoeuvring such as cruise, climb and descent.
- Category C – terminal, involving tight flightpath control such as take-off, approach and landing.

The approach and landing phase of flight has consistently been identified as the most demanding for the pilot. It is within this flight region, where control power is at a minimum, that the pilot is still required to manually manoeuvre the aircraft to fly a narrowly defined flight path. This study therefore focuses on the longitudinal response during the final approach and landing, equating to flight phase Category C.

III Levels of acceptability for mission completion:

- Level 1 – flying qualities are clearly adequate for the mission flight phase.
- Level 2 – flying qualities are adequate to accomplish mission. However, there is an increase in pilot workload, or loss of mission effectiveness.
- Level 3 – the aircraft can be controlled. However, due to significant increase in pilot workload, mission effectiveness is gravely impaired.

The CSAS designer should aim to ensure Level 1 handling qualities when the FBW aircraft is operating in its primary FCS mode. Nevertheless, a lower handling quality level may be deemed acceptable if the aircraft has to operate in a degraded mode (e.g. following the loss of part of the system due to equipment failure).

1.3 Flight control

Flight control laws define the mathematical relationship between pilot input and aircraft control surfaces and hence, aircraft dynamic response. They have traditionally been designed using 'classical' techniques, which provide functional visibility for 'real-world' applications, and are therefore universally accepted by the aerospace industry and regulatory authorities. In addition, predominantly within the research community certain multi-variable control (MVC) law design techniques, such as non-linear dynamic inversion (NDI),

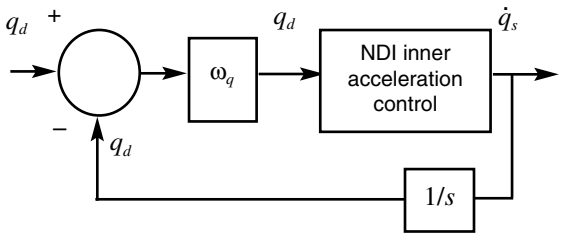


Figure 2. NDI pitch rate control structure.

have proved themselves as very capable flight control law prototyping and analysis tools[12,13].

NDI originated as a non-linear control method over twenty years ago and was further developed for flight control law design and analysis both in the US[14,15] and DERA, specifically as a fast prototyping tool[16]. The versatility of NDI enables the rapid assessment of alternative control configurations and their functionality, and the determination of the control power and command response requirements of both conceptual and established aircraft designs. NDI controllers also enable real-time piloted simulation of a design early in its development cycle and can be used to obtain specifications for control powers and actuator performance. However, until recently, little attention has been paid to handling quality requirements for NDI controllers.

1.3.1 NDI pitch control

The objective of NDI is to cancel the non-linear dynamics of a system through anticipatory control action, resulting in a unity response between all input/output channels. The desired closed-loop dynamics are then superimposed onto each unity response channel. In essence, NDI inner loop control restores stability and enables the user to define the specified dynamic performance in terms of a first order rate response in the rotations about each of the three aircraft body axes. NDI therefore relies on either explicit knowledge, or direct measurement, of specific aircraft parameters. More recently, a realisable form of NDI has been developed which divides the rotational controllers into the three channels and requires far less information at each time step[17]. This form of NDI has been used within this study.

All NDI techniques are based on simple manipulations of the aircraft rotational equations of motion, resulting in a required moment about each axis to generate the commanded rotational acceleration. Using subscripts d and s to signify the demanded and sensed parameters respectively, the inner-loop pitch acceleration control law is:

$$\eta_d = (\dot{q}_d - \dot{q}_s).\frac{I_{yy}}{M_\eta} + \eta_s \qquad \ldots (1)$$

Equation (1) shows that provided the rotational acceleration and control surface position can be measured, the demanded pitch acceleration can be met using a very simple relationship if the pitch inertia, I_{yy}, and control surface effectiveness, M_η, are known accurately at that point in time. By use of the following first-order expression, pitch rate response can be implemented directly:

$$\dot{q}_d = (q_d - q_s)\omega_q \qquad \ldots (2)$$

The term $\dot{q}_d$ can therefore be calculated for use in Equation (1), with the term w_q setting the bandwidth of the response. Thus, the pitch

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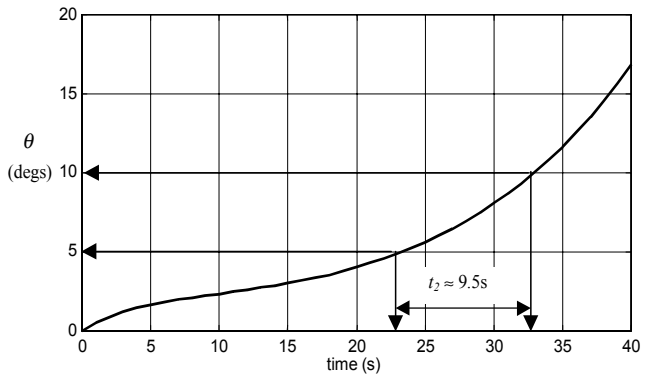


Figure 3. Open loop pitch response to 1° step input.

rate demand, q_d, can be mapped directly into a demanded pitch acceleration, Fig. 2.

The first order case shown here is the simplest means of generating the rate response, however handling quality requirements may dictate a higher-order characteristic. By using the rate commands identified above as inner loops, it is possible to add outer-loop functions to provide alternative response types such as angle of attack, normal acceleration or wind axis roll rate with sideslip suppression[18].

The final control law is implemented in the following form, as a combination of Equations (1) and (2):

$$\dot{q}_d = (q_d - q_s)\omega_q \qquad \ldots (3)$$

The sensed pitch rate q_s and tailplane position hs are generally available on FBW aircraft, with the pitch rate command, q_d, geared directly to the pilot's stick. Careful consideration should be given to the selection of the pitch rate bandwidth, ω_q, to ensure that it is achievable within both airframe and control power constraints.

2.0 UNAUGMENTED DYNAMICS

2.1 Aircraft model

A six-degrees-of-freedom (6-DoF) non-linear mathematical model of the ESCT baseline configuration has been coded in FORTRAN and embedded within MATLAB®/Simulink®. This dynamic simulation and analysis environment provides the numerical integration of model states plus monitoring facilities that are used during development of both the model and flight control laws. Aerodynamic moments and forces are generated by linear interpolation of aerodynamic data tables embedded within the model. The complete aerodynamic data set is valid over an AoA range of 0° to 16°, sideslip of ±8° and a Mach range of 0·2 to 2·0. In addition, aerodynamic lift, drag and pitching moments due to ground effect are modelled as a function of both aircraft height above the ground and attitude. Linear models have been generated using MATLAB linearisation tools with the aircraft trimmed on the final approach to landing. The resulting models have been validated by comparing the time simulation response of selected longitudinal parameters with the non-linear model at the trimmed flight condition[19]. The linear longitudinal models have been used for the off-line open-loop analysis and flight control law design.

2.2 Open-loop dynamics

The relationship between an aircraft response parameter, q, and control input, η, can be represented by a linear transfer function in terms of the Laplace operator, s. For an un-augmented aircraft the denominator of the longitudinal response transfer function will be fourth-order and will dominate the longitudinal response characteristics, with the numerator terms shaping the individual responses. Hence, the pitch rate to elevon transfer function representing ESCT at 155kt on the final approach to land with neutral longitudinal stability is:

$$\frac{q}{\eta}(s) = \frac{-0\cdot584s(s+0\cdot015)(s+0\cdot718)}{(s-0\cdot075)(s+0\cdot861)(s^2+0\cdot276s+0\cdot026)} \qquad \ldots (4)$$

Equation (4) can be compared to equation (5), which defines the individual 'modes' of the system.

$$\frac{q}{\eta}(s) = \frac{k_q s(s+1/T_{\theta 1})(s+1/T_{\theta 2})}{(s+1/T_1)(s+1/T_2)(s^2+2\zeta_{3rd}\omega_{3rd}s+\omega_{3rd}^2)} \qquad \ldots (5)$$

Equations (4) and (5) show that the denominator describing the dynamic modes factorises into two real and one complex conjugate pair of poles. The first pole is positive, therefore unstable and divergent with a time constant, τ, of 13·33 seconds. Noting that:

$$e^{0\cdot7} \equiv 2 = e^{t_2/\tau} \qquad \ldots (6)$$

gives a time to double amplitude, t_2, for the mode of 9·33 seconds. Hence, the unstable mode will dominate the aircraft's long-term dynamic response, but will be slow enough to be controlled by the pilot, see Fig. 3. The second pole is negative, therefore stable and an order of magnitude faster with a time constant of 1·16 seconds. Hence, its effect will only be observable in the first few seconds of the aircraft's response.

The second order term, generally known as the third oscillatory mode, is characterised by short period damping with phugoid like frequency, with the following parameters:

Damping ratio, $\zeta_{3rd} = 0\cdot863$

Frequency, $\omega_{3rd} = 0\cdot16$ rad s^{-1}

Period $T_{3rd} = 2\pi/\omega = 39$ seconds

The long period, combined with the large value of damping, should result in a minimal influence on the longitudinal dynamics.

The numerator term comprises three zeros. A zero located at the origin, which will define the long-term response. The second zero, $1/T_{\theta 1}$ is very slow and therefore has little influence on the short-term manoeuvring response. However, the third zero, $1/T_{\theta 2}$ is much faster and is therefore an important parameter in the assessment of handling qualities. It provides lead and overshoot in the initial pitch rate response compared to that of incidence, which results in a delay known as 'incidence lag', between the pitch attitude and flight path responses.

Relaxed longitudinal stability has resulted in unconventional dynamics on the final approach, which could result in significantly degraded handling qualities. It is at this flight condition, where tight flight path control is required, that the pilot will require the optimum handling qualities to reduce workload and ensure safe operation by achieving an accurate touch-down point on landing.

3.0 HQ DESIGN CRITERIA

Due in part to the increasing application of FBW technology to large civil transport aircraft, recent attention has been given as to how HQ criteria might be used to design FCSs to imbue the aircraft with desirable handling qualities. For example, a comprehensive study by Gautrey[20] addressed these issues and concluded with a specific set of HQ criteria and metrics suitable for CSAS design, which were claimed to provide Level 1 handling qualities regardless of response type. The following criteria and constraints, initially based on Gautrey's findings, have been identified as candidate CSAS design and validation criteria by the author during subsequent research.

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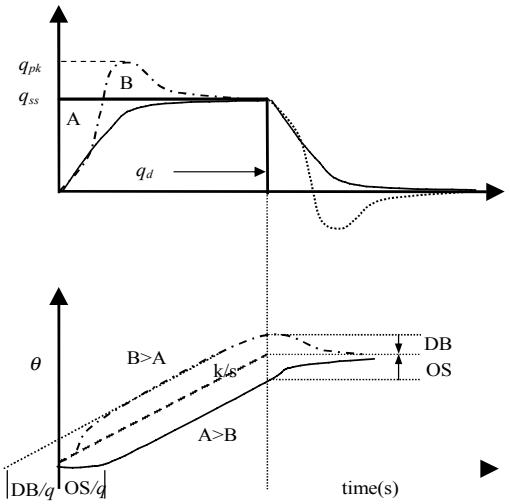


Figure 4. Pitch attitude dropback.

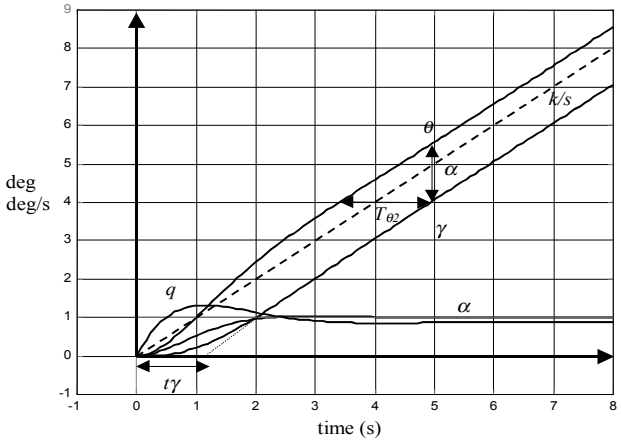


Figure 5. Longitudinal response parameters (Incidence lag).

3.1 Dropback criterion

The pilot's perception of the aircraft's longitudinal handling qualities will be based partly on his ability to accurately predict the final pitch attitude of the aircraft after a stick input. Dropback (DB) is a characteristic of the pitch attitude response and is positive if the attitude decreases to a lower steady value after the control input is removed. The opposite case, where the attitude continues to increase after removal of the input, is known as negative DB or overshoot (OS) with the pitch rate overshoot ratio, q_{pk}/q_{ss} defining the level of DB.

Figure 4 illustrates the variables of interest when defining pitch attitude DB and it can be seen that if the area B>A the pitch attitude will return to a final value, which is less than that when the control demand, q_d, was removed. If the reverse is true, i.e A>B then OS, will result. The value of pitch attitude DB, or OS, is given by the intercept of the back projection of the attitude response plot onto the axis at time = 0 seconds and has units of degrees. The criterion parameter is given in units of seconds requiring dividing through by the steady pitch rate, q_{ss}.

Designing to zero DB will ensure the aircraft behaves like a pure integrator, known as 'k/s like characteristics'. Increasing the DB will improve the pitch attitude and associated flight path response due to a reduction in the flight path time delay. However, excessive values of DB or OS can result in a response which is either too abrupt or too sluggish for the pilot, increasing the difficulty of the task where precision attitude control is required.

The criterion is stated in terms of limiting values on pitch rate overshoot ratio and attitude DB/OS to a steady state pitch rate. The design guidelines on DB are principally based on Mooij's modifications to the original boundaries, as described at reference 1, however, as large values of DB can result in excessive pitch rate overshoot ratio, the upper DB value has been reduced to give a minimum DB of 0 seconds to a maximum of 1·0 second.

3.2 Incidence lag

Ignoring longer-term effects, the transfer function relating pitch attitude response to elevator input using constant speed approximation is:

$$\frac{\theta}{\eta}(s) = \frac{k_\theta(s + 1/T_{\theta 2})}{s(s^2 + 2\zeta_s\omega_s s + \omega_s^2)} \quad \ldots (7)$$

Hence, a classical aircraft's longitudinal short-term attitude response is defined by a dominant zero as well as the familiar short period frequency and damping ratio in the denominator term. For a conventional subsonic aircraft, $T_{\theta 2}$ is determined largely by the value of the wing lift curve slope and is, for all practical purposes, constant throughout the low-speed, low incidence, flight envelope. Therefore, the short-term dynamics are predictable with the transient response governed by the short period mode characteristics. Nevertheless, the magnitude of the zero term, $1/T_{\theta 2}$, has a significant effect on the aircraft's short term longitudinal response: increasing the time constant results in an increase in pitch acceleration, a greater pitch rate overshoot ratio and hence increased attitude DB.

For a conventional sub-sonic aircraft, the flight path response can be represented in a similar manner if we ignore the longer-term and centre of rotation effects:

$$\frac{\gamma}{\eta}(s) = \frac{k_\gamma}{s(s^2 + 2\zeta_s\omega_s s + \omega_s^2)} \quad \ldots (8)$$

Hence, in terms of aircraft longitudinal response, $T_{\theta 2}$ is the effective time lag between the pitch attitude and flight path responses:

$$\frac{\gamma}{\theta}(s) = \frac{k}{sT_{\theta 2} + 1} \quad \ldots (9)$$

Figure 5 shows the unaugmented aircraft's longitudinal response using constant speed approximations and how the flightpath, γ, lags the pitch attitude, θ, by the time constant, $T_{\theta 2}$.

It should be noted that ESCT's tail-less configuration will demonstrate a non-minimum phase, initial opposite-sense, response in normal acceleration greater than a conventional tailplane configured civil transport aircraft[1]. In practice this will add an additional lag to the flight path response; however the fundamental attitude/flight path relationship will still be valid.

3.3 CAP/GCAP criterion

Using the control anticipation parameter (CAP) to constrain the product of $T_{\theta 2}$ and ws to within a set of limits at a specific flight condition, will match the attitude to flight path responses to ensure satisfactory handling qualities.

The original CAP was based on the assumption that the aircraft's short-term response emulates a second-order system, i.e. classical in nature. CAP as a measure of handling qualities was first proposed by Birhle[21] as a means for quantifying longitudinal response to controls, and was developed for precise flight path control and should therefore be applicable to the final approach and landing.

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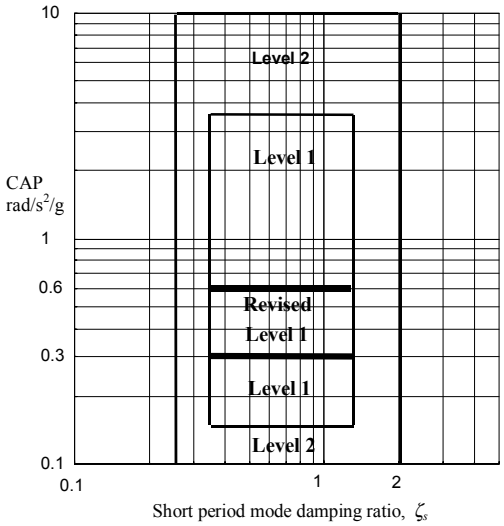


Figure 6. Revised CAP boundaries for large Class III aircraft (Category C).

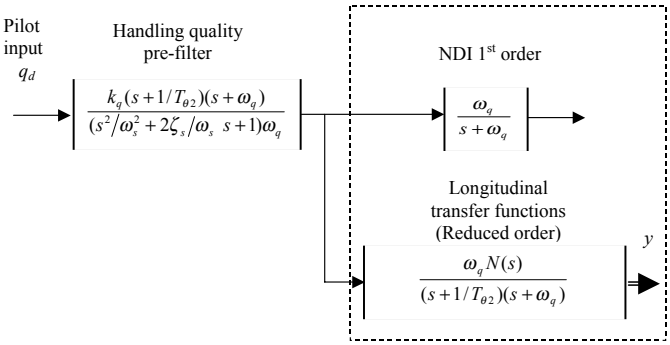


Figure 7. Implementation of HQ command pre-filter.

In essence the criterion defines the relationship between the rotational pitch acceleration and steady state normal acceleration. The formal definition of CAP is 'the amount of instantaneous angular pitching acceleration per unit of steady state normal acceleration'. It may be shown that:

$$CAP = \frac{\dot{q}(0)}{n_z(\infty)} = \frac{g\omega_s^2 T_{\theta 2}}{U_e} = \frac{\omega_s^2}{n\alpha} \quad \ldots (10)$$

Where n_α is the normal load factor per unit AoA:

$$n_\alpha \cong \frac{U_e}{gT_{\theta 2}} \quad \ldots (11)$$

Typical values for n_a and $T_{\theta 2}$ are associated with classical aircraft and are governed by the wing loading and lifting properties of the airframe. Nevertheless, it can be seen that CAP is very much dependent on the short period frequency, ws, and incidence lag, $T_{\theta 2}$.

CAP in its original form was based on the dynamics of conventional aircraft and is therefore strictly only applicable to aircraft possessing classical dynamics. However, generic CAP (GCAP) has been proposed by Gautrey[20] for application to command laws with rate-like characteristics in the short-term. Nevertheless, it is required that the normal acceleration response is fundamentally second order like with the dynamics principally defined by the short-term parameters.

The original boundaries on acceptable CAP were necessarily broad to accommodate the large variation in Class III aircraft mass, from 35,000kg to 350,000kg, as shown below for Level 1 handling qualities.

$$0{\cdot}16 \text{ rad/s}^2/\text{g} \le CAP \le 3{\cdot}6 \text{ rad/s}^2/\text{g}$$

Gautrey proposed modifying the original boundaries, based on the findings of Mooij[22] and his own research.

$$0{\cdot}3 \text{ rad/s}^2/\text{g} \le CAP \le 0{\cdot}6 \text{ rad/s}^2/\text{g}$$

The modified boundaries have been added to the original constraints shown in Fig. 6.

The CAP/GCAP criterion, using the modified constraints for large Class III aircraft during Category C flight, is to be applied during the design of the CSAS for the ESCT. A range of suitable short-term frequencies can be calculated using the revised CAP constraints, the un-augmented aircraft's $T_{\theta 2}$ and the CAP equation[10]. For verification, GCAP can be calculated from a time simulation.

4.0 FLIGHT CONTROL LAW DESIGN

4.1 Pitch rate command

A pitch rate command law is ideal for precise attitude control and requires a minimum number of sensors to implement. For these reasons, it is a popular command type for both military and civil aircraft. NDI pitch rate control (Equation (3)) requires the specification of a response bandwidth, wq, which, to ensure sufficient attitude and flightpath bandwidths has been set at 1·5 rad s^{-1}. Hence, NDI control of the open-loop, rigid body, dynamics, as defined by Equation (4), results in the following pitch rate response to command transfer function:

$$\frac{q_s}{q_d}(s) = \frac{1{\cdot}5s(s+0{\cdot}015)(s+0{\cdot}718)}{s(s+0{\cdot}015)(s+0{\cdot}718)(s+1{\cdot}5)} rad\ s^{-1}/rad\ s^{-1} \quad \ldots (12)$$

which equates to:

$$\frac{q_s}{q_d}(s) = \frac{\omega_q s(s+1/T_{\theta 1})(s+1/T_{\theta 2})}{s(s+1/T_{\theta 1})(s+1/T_{\theta 2})(s+\omega_q)} \quad \ldots (13)$$

Equations (12) and (13) illustrate how NDI control results in exact cancellation of the three zeros at $1/T_{\theta 1}$, $1/T_{\theta 2}$ and at the origin, by corresponding poles. After cancellation the resulting first order transfer function is:

$$\frac{q_s}{q_d}(s) = \frac{1{\cdot}5}{s+1{\cdot}5} \text{rad s}^{-1}/\text{rad s}^{-1} \quad \ldots (14)$$

From equation (14) it can be seen that the frequency response will demonstrate a maximum –90° of phase shift at high frequencies due to the single pole. In addition, there will be 20dB/decade attenuation of the response above the 15 rad s^{-1}cut-off frequency. Actuator dynamics will contribute to the effective system order and authority limits will add magnitude and frequency dependent non-linear effects. Hence, the first order linear response is 'ideal', however, it is a good basis from which to develop the final control law.

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4.2 Response shaping

NDI rate control as the inner core of the control law restores stability, augments the response and provides the pilot with direct control of the pitch rotational parameter. However, positive DB requirements and associated pitch rate overshoot ratio indicate that a greater than first order pitch response may be required to ensure Level 1 handling qualities.

A higher-order response can be synthesized by pre-filtering the pilot's input using a second order transfer function with an additional zero, $1/T_{\theta 2}$, to shape the NDI pitch response. The pre-filter will also consist of a lead term to cancel the NDI first order response, equation (15).

$$\frac{(s+1/T_{\theta 2})(s+\omega_q)}{(s^2+2\zeta_s\omega_s s+\omega^2)\omega_q} \quad \ldots (15)$$

The pre-filter is placed outside the inner feedback loop in the pilot's command path and therefore has no effect on the closed loop stability. However, an additional effect of NDI inner loop control is to add a short-term pole, with a time constant equivalent to $T_{\theta 2}$, to the other longitudinal transfer functions, see Fig. 7.

Hence, implementation of the pre-filter will result in a higher than second order short-term normal acceleration response, which implicitly defines the flight path response characteristics. It has also been argued that it is important to 'match' the pitch and flight path dynamics, if desirable handling qualities are to be assured, as $T_{\theta 2}$ effectively defines the relationship between the pitch attitude and flight path responses. The pre-filter pitch attitude zero should therefore be set to the un-augmented aircraft's $T_{\theta 2}$ to cancel its effect on the short-term dynamics of all the longitudinal transfer functions. Hence, the design's short-period mode restores essentially 'classical' short-term manoeuvre characteristics to the other important longitudinal response parameters, equation (16).

$$\frac{y}{q_d}(s)=\frac{k_q(s+1/T_{\theta 2})(s+\omega_q)}{(s^2/\omega_s^2+2\zeta_s/\omega_s s+1)\omega_q}\frac{\omega_q N(s)}{(s+1/T_{\theta 2})(s+\omega_q)}$$

$$\frac{y}{q_d}(s)=\frac{k_q N(s)}{(s^2/\omega_s^2+2\zeta_s/\omega_s s+1)} \quad \ldots (16)$$

4.3 Designing to CAP

The pitch attitude zero, $1/T_{\theta 2}$ and the short period damping ratio, ζ_s have been set at 1·393 seconds (the un-augmented value at the trim conditions) and 0·7 (ideal value) respectively. The remaining pre-filter parameter, equating to the short period frequency, has then been calculated using the CAP equation (10) constrained to the original (0·16 to 3·6 rad/s^2/g) and revised (0·3 to 0·6 rad/s^2/g) Level 1 CAP boundaries.

Figure 8 shows the calculated short-period frequencies, ws together with the associated pitch rate overshoot ratio, q_{pk}/q_{ss} and pitch attitude DB for both the revised (in white) and original CAP boundaries (in grey). The results indicate that:

- The low frequency pre-filter 1 results in negative DB, defined by the small pitch rate overshoot ratio.
- The pre-filters designed to the revised constraints (in white) and pre-filter 2 satisfy all the guidelines.
- Pre-filters 6 and 7 designed to high CAP result in large short-term frequencies, which generate excessive pitch rate overshoot ratios.

5.0 VERIFICATION AND VALIDATION

The NDI flight control laws have been implemented using the recommended handling quality design criteria defined previously. Real-time, pilot-in-the-loop, simulation using the full non-linear 6-DoF model has been used to verify the design process and confirm that the pre-filters designed to the revised CAP constraints provide Level 1 handling qualities.

5.1 Simulation environment

The trials were performed on DERA Bedford's two-seat, fixed-base, civil aircraft research flight simulator. The facility comprises principally of a PC based real-time simulation environment including a full flight envelope mathematical model configured and controlled via an integrated operator station. The simulator has been updated to include user configurable electronic flight instrumentation system (EFIS) head down and multifunction display, immersive visuals and side-stick controllers[1].

5.2 Evaluation tasks

As civil transport pilots have traditionally controlled the aircraft's flight path through pitch attitude, a pitch attitude capture task has been selected to quantify the aircraft's pitch sensitivity. Additionally, a vertical off-set, precision final approach and landing task has been used to enable the pilot to close the feedback loop around flight path and therefore ensure a satisfactory level of handling qualities and that the aircraft can be operated and flown safely. Both tasks require the baseline ESCT aircraft initialised at its final approach airspeed of 155kt, auto-throttle engaged, and four nautical miles (nm) from the runway threshold at an altitude of 900ft.

The assessment was required to quantify the aircraft's performance using standard criteria, metrics and pilot comments. Two experienced commercial transport aircraft flight test pilots (A and B) provided both quantitative and qualitative assessment using the familiar Cooper-Harper (CHR) and pilot induced oscillation (PIO) rating scales[1].

	Pre-filter	CAP (rad/s^2/g)	Pre-filter parameter			q_{pk}/q_{ss}	DB(s)
			ζ_s	$T_{\theta 2}(s)$	ω_s(rad/s)		
	1	0·16	0·7	1·393	0·97	1·20	–0·05
	2	0·25	0·7	1·393	1·20	1·30	0·20
Design	3	0·30	0·7	1·393	1·32	1·37	0·35
CAP	4	0·45	0·7	1·393	1·62	1·53	0·50
constraints	5	0·60	0·7	1·393	1·87	1·68	0·65
	6	1·00	0·7	1·393	2·50	2·15	0·80
	7	3·60	0·7	1.393	4·50	3·44	1·10

Figure 8. Pre-filters table.

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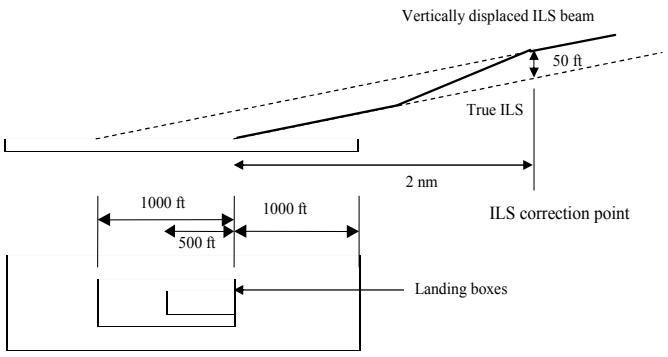


Figure 9. Pitch off-set correction & landing task.

5.2.1 Pitch attitude capture

- From trim attitude pull the stick back to capture 5° pitch attitude increment.
- Regain original trim attitude.
- Push stick forward to capture –5° pitch attitude increment.
- Regain original trim attitude.

Assessment criteria

Based on pilot comment for this study:

- Desired performance is defined as 'achieving the commanded attitude to within ±1° after removal of initial control input'.
- Adequate performance is defined as 'achieving the commanded attitude to within ±2·5° after removal of initial control input'.

There is an additional 3 to 4 second time limit on execution of the manoeuvre while constraining normal acceleration to between 0·6 to 1·4g.

5.2.2 Pitch offset manoeuvre and landing

- Intercept the instrument landing system (ILS) beam on a -3.0° glide slope at approximately 3nm and an altitude of 900ft from the runway threshold.
- Follow the ILS beam until emerging below the cloud-base at 2nm from the runway threshold. When flying under visual conditions correct for an approximate 50ft vertical offset from the true ILS indicated by the precision approach path indicators (PAPIs) showing four whites.
- With the aircraft stabilised on the final approach, commence the flare. Disconnect the auto-throttle and manually retard the engines to reduce speed upon reaching the flare attitude. To reduce the sink rate adequately within the aircraft's geometric pitch attitude limits an early, shallow flare may be required. An overall attempt to touchdown in the inner, desirable landing box should be made, Fig. 9.

Assessment criteria

Based on pilot comment for this study:

- Desired performance is defined as 'maintaining flight path to ±1 dot (glide slope deviation) and landing at a sink rate not exceeding 3ft/s'.
- Adequate performance is defined as 'maintaining flight path to ±2 dots and landing at a sink rate not exceeding 6ft/s'.

In addition, to increase task urgency landing boxes were provided to constrain the touchdowns.

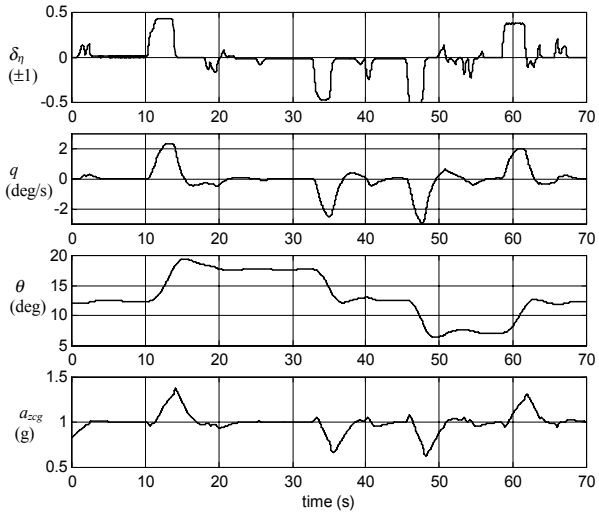


Figure 10. Pitch attitude capture task.

5.2.3 Meteorological conditions

All pitch attitude capture tasks were flown in steady and visual conditions. The approach and landing tasks were flown in visual conditions after emerging beneath a 600ft cloud-base 2nm from the runway threshold. Selected approach and landing tasks were also flown in turbulence.

5.2.4 Trial aims & objectives

In summary, the aims and objectives of the piloted simulation trials were to:

I. Verify the pre-filter design process and validate the modified CAP constraints considering:
   - Pitch sensitivity;
   - Pitch attitude capture.

II. Quantify command law performance and characteristics during the final approach and landing considering:
   - Tight flight path control;
   - Flare and touchdown performance;
   - Meteorological conditions.

5.3 Task analysis

The pitch attitude capture task was used to verify the pre-filter design process and validate the modified CAP constraints. A typical longitudinal response using an example pre-filter has been plotted, see Fig. 10.

The pilot initiates a pitch rate command via a positive stick input at 10 seconds while restricting the resulting normal acceleration to the 1·4g maximum limit. The subsequent 2·5°/s pitch rate response corresponds to a steady increase in pitch attitude. There is also an increase in normal acceleration after the initial opposite sense response due to non-minimum phase behaviour. At approximately 14 seconds the pilot returns the stick, commanding zero pitch rate, which results in the pitch attitude dropping back after a 2° to 3° overshoot. The normal acceleration is also seen to return to 1g after a slight initial increase due again to non-minimum phase behaviour. At approximately 33 seconds into the simulation the pilot repeats the command in the opposite direction, restricting the normal acceleration to within the 0·6g minimum constraint and completing the manoeuvre just before 60 seconds after which he returns the aircraft to its trim condition.

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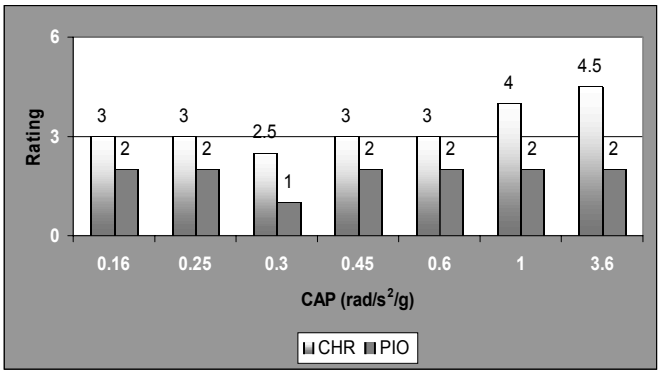


Figure 11. Pre-filter assessment – Pilot A.

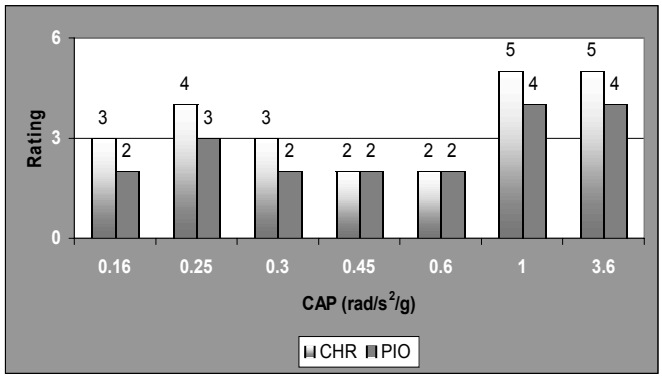


Figure 12. Pre-filter assessment – Pilot B.

5.3.1 Pre-filter assessment

The seven pre-filter designs were implemented by adjusting the short-term frequency, ws whilst retaining constant short-term damping ratio ζ_s of 0·7 and pitch attitude zero $T_{\theta 2}$ of 1·393 seconds. Pilot A and B's CHR and PIO ratings for each pre-filtered response are shown in figures 11 and 12 respectively. The boundary delineating Level 1 (CHR≤3) from Levels 2 and 3 (CHR>3) has been plotted.

Although the lower CAP designs were predominantly rated as Level 1, they were judged to be very sluggish, requiring 2º to 3º of pilot anticipation to achieve the target pitch attitude. In addition, a noticeable pitch attitude overshoot and attendant sluggish response required significant pilot anticipation to achieve successful pitch attitude captures. Nevertheless, the response was rated as predictable with very little tendency for the aircraft nose to bobble or nod. The pilots also stated that the slow pitch acceleration of the lower CAP designs resulted in the aircraft being unable to achieve more than 1·2 g, less than the maximum specified 1·4 g, before having to reverse the input in order to capture the target pitch attitude.

Pre-filters 3 to 5, designed to the revised CAP constraints of 0·3 to 0·6 rad/s^2/g, were awarded the best CHR and PIO ratings by both pilots. The fast and predictable response characteristics, with little or no tendency to pitch bobble or nod, together with obvious pitch attitude DB increased the CHR, consistently equating to Level 1 handling qualities. In addition, the predictability of the response eliminated the pilot's need to overcorrect during the final approach and flare, as with the other command laws.

Increasing CAP and therefore, short-term frequency improves the speed of response, progressively requiring less anticipation by the pilot in order to capture the target pitch attitude. However, as CAP approaches 1 rad/s^2/g the response becomes far too sensitive resulting in difficulty in controlling pitch attitude, hence the general degradation in both CHR and PIO ratings, equating to Level 2 handling qualities.

The generally higher PIO ratings awarded by Pilot B can be attributed to his 'higher gain' piloting technique, which could trigger significant overshoot and oscillation in the response as he entered the control loop. However, Pilot A was far more likely to fly 'open-loop' and hence avoid triggering any high frequency PIO tendencies.

In addition, pilot comments and further analysis suggested that:

- The pilots accepted a slightly more sluggish response than predicted by the revised CAP constraints due to allowances for very large aircraft dynamics.
- The sluggish response of the low CAP configurations makes the use of significant pilot aggression difficult. Hence, pulling more than 1·2g is not possible before the pilot requires anticipatory recovery input.
- With the best designs it was required to stop the command input at 0·5° before reaching the target pitch attitude, resulting in an overall faster response.
- As frequency increases, more pilot anticipation is required resulting in greater 'pilot perceived' overshoot. Generally, a CAP greater than 0·6 rad/s^2/g generated excessive overshoot, equating to q_{pk}/q_{ss} greater than 2.
- At highest frequencies a much more sensitive response was experienced.

5.3.2 Flight path control

A typical pitch offset correction and landing task, using an example pre-filter, has been plotted, see Fig. 13.

With the aircraft flying straight and level at 900ft, the pilot applies a couple of positive pulse like stick inputs to stabilise the aircraft. At approximately 34 seconds the aircraft intercepts the –3º glide slope requiring a series of forward stick inputs to capture and then follow the glide slope. The initial decrease in AoA results in the required flight path change, observed on the height plot, which then settles out at the final approach trim pitch attitude. At approximately 90 seconds the pilot applies several aft stick inputs of increasing amplitude to initiate a slight flare, shown by an increase in attitude and AoA which is required to arrest the sink rate to acceptable levels. After touchdown a large, forward stick input is required to lower the nose of the aircraft and complete the landing.

For the assessment, both pilots assigned CHRs between 2 and 3, equating to level 1 handling qualities, to all stages of the task. The command laws were judged easy to fly due to accurate flight path and flare control resulting in consistently predictable touchdowns with correspondingly desirable sink rates, i.e. well within the ≤3ft/s upper limit at an approximate 140kt touchdown speed and with little perceptible aircraft float.

The pitch rate command laws also performed well in turbulence. The attitude hold characteristic of the command law minimised pitch deviations, suppressing the most dominant cue on a fixed base simulator. The reduced pitch activity encouraged the pilot to stay out of the control loop therefore reducing his workload and improving his handling quality ratings. Flight path control was rated more difficult in turbulence, degrading the CHRs by 1·5, over those awarded in steady conditions.

It was clear that the pilots rated the handling qualities predominantly on the short-term, frequency defined, pitch acceleration response. This was in part due to the 'visual' pitch response being by far the strongest cue on a fixed base simulator. Due to the absence of motion the only indication of normal acceleration, and by definition flight path rate, was provided by the numerical 'g' meter on the head down display (HDD).

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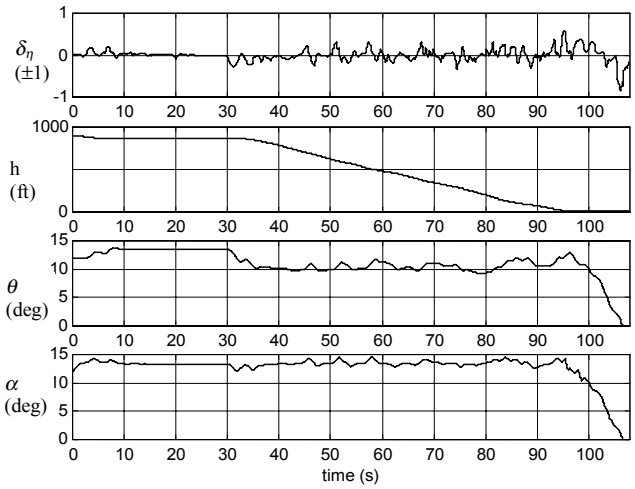


Figure 13. Final approach and landing task.

CONCLUSIONS & RECOMMENDATIONS

- Relaxed longitudinal stability has resulted in unconventional dynamics on the final approach, which could result in significantly degraded handling qualities. It is at this flight condition, where tight flight path control is required, that pilot workload will be high.
- A set of CSAS design criteria and guidelines suitable for a second-generation SST during the terminal phase of flight have been proposed. They were based on the handling quality investigation together with the results and recommendations from previous research.
- The augmented short-term pitch response must be representative of the class and mass of aircraft and matched to the aircraft's inherent flight path response to ensure desirable handling qualities. Satisfaction of CAP/GCAP implicitly takes account of this relationship due to the requirement on pitch acceleration and steady state normal acceleration.
- NDI inner loop control has the capability to restore stability and provide a first order rate response within control power constraints. A pitch rate command system can consistently provide Level 1 handling qualities during the final approach and landing (Category C operations).
- Pre-filtering the pilot's input to provide a second-order pitch rate response using the suggested parameters and the revised CAP constraints will generate the best overall handling qualities. The resulting pre-filter can be easily applied to NDI inner loop controllers and is straightforward to implement with simple, practical and proven sensor requirements.
- To ensure Level 1 handling qualities for a very large SST in the terminal phase of flight the upper and lower limits on CAP should be revised, the short-term mode damping ratio set to 0·7, and an ideal CSAS 'design point' taken as midway between the upper and lower limits. The revised boundaries for large Class III aircraft during Category C operations are:

- Hence, to summarise, the steps in the preliminary pre-filter design process are:

(*i*) Obtain value for $T_{\theta 2}$ from the baseline linear model at the specific design point.

(*ii*) Set frequency of pre-filter pitch attitude zero to $1/T_{\theta 2}$.

(*iii*) Set damping coefficient to 0·7 for ideal damping.

(*iv*) Calculate short-term frequency using CAP expression combined with modified design constraints on CAP of 0·3 to 0·6 rad/s^2/g.

(*v*) Verify time response using step input and calculated GCAP.

- The addition of the pitch attitude zero at $1/T_{\theta 2}$ also increases both the pitch attitude and flight path bandwidths of the pre-filtered system, over the first-order implementation, improving the overall aircraft response.
- Motion-based simulation would provide normal acceleration cues in addition to visual cues. This would enable the pilot to better compare the pitch attitude to flight path change response hence improving overall assessment validity.
- It would be appropriate to perform similar evaluations of smaller Class III transport aircraft with associated dynamics to provide confirmation of the CSAS design process and identify where the author's modified CAP constraints may require further revision.

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