ADVANCES IN PARTIAL AUTHORITY FLIGHT CONTROL AUGMENTATION

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Abstract

In pursuit of increased mission effectiveness under day/night all weather conditions, DERA has been exploring concepts for affordable automatic flight control system upgrades for the current generation tri-service helicopter fleet. This paper details a series of ground-based and in-flight simulation experiments exploring the implementation issues and operational benefits arising from application of limited authority attitude command and translational rate command response types. In particular, the requirements for series and parallel actuation have been investigated and the resulting handling qualities improvements for various response type/ actuation configurations have been assessed.

Introduction

Handling Qualities and Mission Effectiveness

Handling qualities are a measure of the ease and precision with which a pilot is able to perform a particular mission task. Formal requirements on handling qualities are specified in terms of three "Levels" of acceptability relating to task performance and pilot workload as shown on the Cooper-Harper Pilot Rating Scale (Ref. 1).

Most, if not all, current military helicopters can only achieve Level 2 handling qualities in degraded visual environment (DVE) conditions for the most critical mission tasks, and can degrade to Level 3 in exceptional circumstances. Deficiencies which impact on the perceived task performance include control system-related attributes such as poor static and dynamic stability, strong cross couplings, together with external factors such as strong atmospheric disturbances. Pilots can overcome many of these problems in normal flying conditions, but when operating in a high threat environment, degraded visual conditions or confined areas, the flying task can consume all of the pilot's spare capacity. This significantly reduces the pilot's situational awareness, degrades the mission effectiveness, and compromises flight safety.

The rotorcraft handling qualities standard ADS-33 (Ref. 2) recognises the importance of the visual conditions by promoting the innovation of the usable cue environment (UCE) whereby the visual scene content is categorised in terms of its utility to the pilot in performing a specific mission task. The UCE categorisation will fall into one of three levels with a UCE of 3 being the poorest. Given a task/UCE combination, ADS-33 defines the minimum requirements, in terms of control response types and dynamic response criteria, necessary to achieve Level 1 handling qualities. Table 1 summarises the characteristics of the three levels of UCE and their implication on response requirements.

UCE	Characteristics	Response Type
1	GVE typical of clear daylight flight over well-defined terrain	Rate Command (RC) or Rate Command, Attitude Hold (RCAH)
2	DVE typical of moonless night while using NVGs	Attitude Command, Attitude Hold (ACAH)
3	DVE typical of overcast moonless night with NVGs	Translational Rate Command, Position Hold (TRC/PH)

Table 1
Minimum Response Requirements for Level-1 Handling Qualities in Various UCEs

Clearly where operations in DVE conditions are envisaged, increased control augmentation will be essential for providing the necessary level of handling qualities that allow mission tasks to be performed with agility and safety.

Partial Authority Flight Control Augmentation

Providing the augmentation required for optimum handling qualities in all conditions is generally considered to be best achieved through full-authority FBW/ACT, whereby the pilot's commands are electrically or optically communicated to a flight control computer, which in turn synthesizes the appropriate collective and cyclic blade pitch demands. If Level 1 handling qualities are to be conferred on current in-service helicopters, then cost constraints will likely dictate that the equivalent functionality of a highly augmented FBW/ACT system will have to be sought within the bounds of the existing flight control system architecture.

The Primary Flight Control System (PFCS) typically consists of hydraulically boosted mechanical linkages (e.g., push-rods, bellcranks, cables, etc.) that connect the cockpit controls directly to the swashplate actuation system. Augmentation of the basic handling qualities is then achieved through the Automatic Flight Control System (AFCS) which can provide feed-forward command shaping and/or attitude and rate feedback stabilisation via limited authority, high rate series actuators and autopilot hold and guidance functions via limited-rate, high-authority parallel actuators.

Thus, the objective of partial authority flight control augmentation (PAFCA) is to achieve maximum synergy from integration of the AFCS with the force-feel system, feedback sensors and series and parallel servos, particularly with respect to tailoring of the limited authority response type (LART) control laws.

Previous PAFCA Studies

The consideration of ADS-33 handling qualities requirements was originally examined purely in the context of full authority FBW/ACT. However, in recent years considerable progress has been made in developing an understanding of the potential for handling qualities improvement using partial authority augmentation.

A key study in this area was performed by Baillie et al (Ref. 3) who describe an in-flight evaluation of LART control laws using the NRC Bell 205 Airborne Simulator. The handling qualities ratings (HQRs) and comments suggested that a LART ACAH system could provide borderline Level 1 handling qualities for hover/low-speed tasks in a DVE. An important observation was that series servo saturation did not always result in degraded handling qualities and could actually assist aggressive manoeuvring.

More recently a series of ground-based simulation studies have been conducted jointly by DERA and the US Army AFDD. An initial study investigated further the impact of AFCS saturation on handling qualities in ADS-33 hover/low-speed flight test manoeuvres (Ref. 4). It was found that to avoid AFCS saturation, ±35 % pitch and ±25 % roll AFCS authority was required. (Note that these data relate to the maximum manoeuvre capability of an ACAH response type, with no auto-trim follow-up, in good visual conditions and with no prevailing atmospheric disturbances.) It was also seen that saturation was not always detrimental and borderline Level 1 handling qualities ratings could be achieved, even at maximum aggression, with a ±25 % pitch and a ±15 % roll AFCS limit. This point reinforced the findings of Ref. 3. Further, the data suggested that pilots were not perceiving saturation as such, but rather the magnitude and/or phase of the model-following error resulting from saturation. Additional simulation testing showed that matching the augmented and unaugmented dynamics in the frequency range of the pilot-aircraft closed-loop crossover resulted in more benign and predictable saturation characteristics. The concept of frequency matching was thus demonstrated to offer significant potential as a design philosophy for optimisation of partial authority AFCS.

A subsequent ground based simulation study, conducted by the same research team, considered the impact of series servo saturation on handling qualities in moderate aggression hover/low-speed manoeuvres in a DVE (Ref. 5). This study confirmed the original conclusions with regard to the benefits of frequency matching and, since the candidate platform featured a significantly different rotor system from that used in the original work, also established the generic applicability of the approach. As part of this study an assessment of the impact of series servo hardovers was also conducted in which it was demonstrated that all failures were recoverable and tolerable for a ±15% authority system.

Another recent study has combined the handling benefits of PAFCA augmentation with a relative GPS guidance solution for helicopter-ship recovery in adverse environmental conditions. Once more the concept demonstrated significant safety and operational effectiveness benefits. (Ref. 6)

Study Objectives

At the conclusion of the studies described above, several areas for further research remained. The lessons learned related primarily to implementations of a single response type, ACAH. Reference to Table 1 reminds us that, for the more severely degraded environments characterised by UCE=3, the minimum response type requirement mandated by ADS-33 is the higher order Translational Rate Command (TRC) and hence there remained a need to investigate implementation of TRC within the partial authority framework. In addition, there was also a need to quantify better the influence of wind and turbulence on such systems.

Finally, the major findings regarding the implementation of ACAH were limited to ground-based simulation and there was consequently a desire to validate any resulting recommendations and design guidelines by transitioning the concepts to in-flight demonstration.

Thus the objectives of this study were as follows

- To design a partial authority control law for a support helicopter providing both ACAH and TRC response characteristics.
- To conduct handling qualities evaluations of the two response types in a simulated DVE and disturbance environment.
- To develop an in-flight simulation of a partial authority frequency matched ACAH implementation on an experimental variable stability rotorcraft.
- To conduct in-flight assessment of the PAFCA ACAH control law with the aim of validating benefits identified in ground-based studies, i.e. reduced series servo activity, delayed onset of series servo saturation and improved predictability of control upon saturation
- To implement and conduct exploratory in-flight investigation of a partial authority TRC response type.

In pursuing these objectives it was intended that the overall knowledge base on the design PAFCA systems would be further expanded, with particular applicability to enhancing operability in DVE.

Description of PAFCA systems

Control System Architecture

The PAFCA system architecture used in both simulation and flight activities broadly followed that used in the previous DERA/AFDD studies (Refs. 4-5). The hydro-mechanical PFCS is assumed to be conventional in structure and remains unmodified by application of the PAFCA control laws. It is the aim of the PAFCA system to provide a level of functionality equivalent to a highly augmented FBW/ACT system - *i.e.* high bandwidth, task-tailored control - and to this end the AFCS is configured with a two degree-of-freedom, explicit model-following architecture (Ref. 7). An overview of the system architecture is shown in Figure 1.

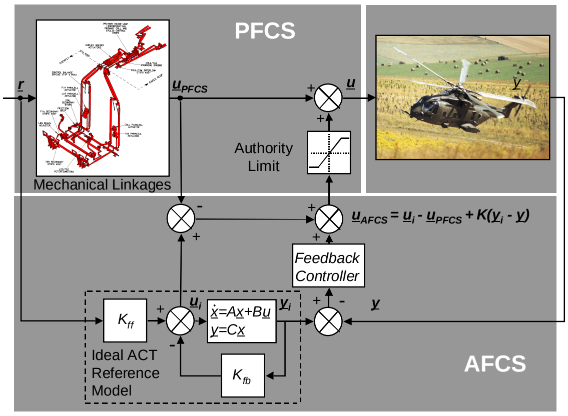


Figure 1
PAFCA Control System Architecture

Dynamic feed-forward command augmentation, based around an idealised full-authority reference model, is coupled with proportional, integral and derivative (PID) attitude feedback stability augmentation. The idealised full-authority reference model is based around a 6 degree-of-freedom reduced order linear model of the aircraft. A full-state feedback control law is synthesised around this open-loop model with the objective of conferring the desired response type, command tracking, and dynamic decoupling.

The control law design methodology chosen to synthesise this controller is not critical, a number of modern mutlivariable design techniques having been applied. However, in recent work a form of non-linear dynamic inversion, or NDI, (Ref. 8) has been favoured since it allows the engineer to prescribe directly the closed loop response characteristics.

Theoretically, this feedforward command reference model computes the ideal blade angle demands to achieve perfect model following, but a feedback controller is always necessary to attenuate errors resulting from external disturbances, nonlinearities and model inaccuracies.

Attitude Command Augmentation

It has been be shown that matching the gain and phase of the command model dynamics to the unaugmented aircraft dynamics in the region of the task bandwidth/closed-loop crossover frequency (*i.e.* $1.0 \text{ rad/s} < \omega < 10.0 \text{ rad/s}$) will minimise the transients in aircraft behaviour upon saturation. This will also focus available control effort on stabilisation of the low frequency modes and inter-axis decoupling.

Application of the NDI control methodology to the low order linear model effectively reduces the command model to the decoupled system shown conceptually in Figure 2, for which the designer need only specify a control power, and the frequency and damping of the second order attitude response. The control power is specified to meet sensitivity requirements whilst the dynamic variables are submitted to an optimisation tool with the objective of maximising the frequency match.

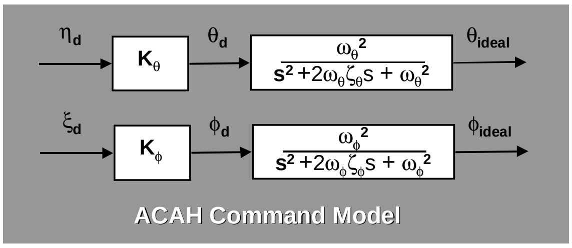


Figure 2
Command Model Variables for ACAH

Clearly the handling qualities characteristics resulting from frequency-matching will be strongly dependent on the inherent bandwidth and control power of the rotor system. For an aircraft with a moderate/high hinge offset there is a good probability that the handling qualities of the augmented aircraft will be satisfactory. This assessment obviously needs to be performed against ADS-33 open- and closed-loop requirements with the pilot-in-the-loop to determine the acceptability of the handling qualities and the saturation characteristics.

Translational Rate Command Augmentation

Early implementations of TRC considered in this study paralleled that of ACAH in that the demanded response speed was proportional to the displacement of the cyclic stick. However, the issues associated with series actuator saturation whilst operating in TRC mode differ significantly from those encountered in ACAH. With an appropriately optimised system, such as that provided by frequency matching, the transition from attitude command to the rate response characteristics of the raw airframe can be relatively benign. When saturation occurs the pilot is typically operating at frequencies at which the closed loop ACAH response exhibits similar characteristics to the rate command response type of the unaugmented aircraft and it is intuitive for him to apply corrective inputs that return the aircraft to a controlled state. In the transient period of saturation the quickening of the response can actually be beneficial, providing additional agility in aggressive manoeuvring.

In TRC saturation is likely to occur during the acquisition of a new speed, a phase during which the aircraft attitude and angular rates will be varying automatically under the actions of the control system. The pilot is thus unlikely to make rapid diagnosis of a transition from these controlled rates to those of unstabilised aircraft and large attitudes can develop before corrective action can be taken. The situation is particularly acute in degraded visual conditions.

Consequently when implementing a partial authority TRC system the objective becomes the prevention of saturation rather than the management of the transient. There is thus a need to introduce an auto trim follow-up functionality that harnesses the limited rate parallel actuators with the aim of maintaining the series actuators close to the centre of their limited authority. The architecture applied in the current study is shown in Figure 3.

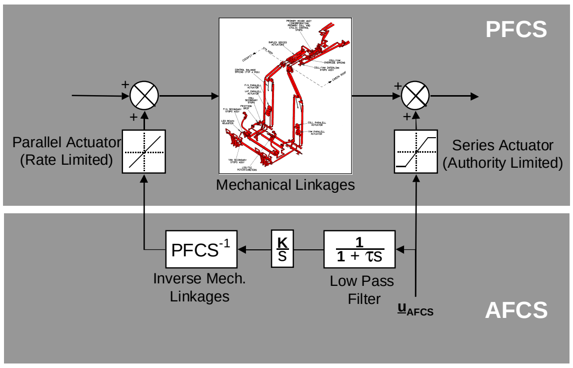


Figure 3
Auto-trim Follow-up Architecture for PAFCA TRC

In this implementation the AFCS blade angle demand, $\underline{u}_{AFCS}$, continues to drive the limited authority series actuators, but a low frequency element is used to generate a parallel actuator demand. Consequently, longer-term blade angle demands are accommodated by the PFCS, maximising the ability of the AFCS to respond to high frequency stabilisation and manoeuvre demands.

The negative aspect of using the parallel actuators is that the pilot experiences uncommanded movement of the cyclic stick datum. Since it is this datum from which the stick has been offset to generate the speed demand, pilots tend to find such an implementation confusing and undesirable. Consequently an alternative implementation of TRC was proposed in which the pilot's command is generated via the beep trim switch located at the stick top. By so doing the pilot can maintain a constant input to the control system whilst the stick datum is driven under his hand as the parallel actuators act to inhibit saturation.

In common with the ACAH implementation the dynamic response of the TRC system is also governed by the command model. An additional feedback loop is first introduced around the extant ACAH system as is shown conceptually in Figure 4. The value of the variable K_v is then tuned to achieve a first order like response to a translational rate demand. The rise time of the response is limited by the dynamics of the inner loop attitude control.

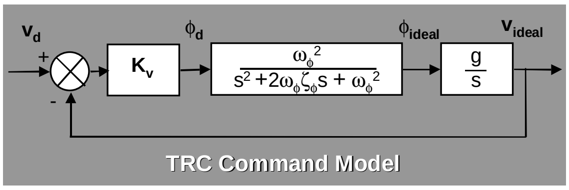


Figure 4
Command Model Variables for TRC

Typically the extant beep trim switches available on the inceptors of both in-service aircraft and flight simulation facilities are of a digital functionality. In the context of a TRC implementation, this attribute limits the degree to which the pilot can control the velocity demand v_d. The simplest option is to generate a step demand on depression of the trimmer and return to a hover demand on centring. The advantage of this mechanism is that the pilot has tactile cueing of his demand and can thus operate without reference to displays. However, only one speed can be demanded and, in order to restrict the attendant attitude excursion, its magnitude must be low (< 10kn) - large uncommanded attitude changes being considered undesirable in DVE.

A greater degree of speed control is provided by integrating the signal from the trim switch to generate the speed command – i.e. translational acceleration control (TAC). Such a system can be used to command significantly larger translational rates and obviates the need for the pilot to maintain a force on the trim switch for extended periods of time. However, this implementation must be integrated with a display to inform the pilot of his demand since returning the trim switch will result only in maintenance of current speed. The addition of a hover-capture facility is a useful addition to such a system, thus enabling the pilot to drive the speed demand to zero at the push of a button. The concept of implementing TRC and TAC on a multi-way analogue trim switch has been demonstrated to great effect on the DERA VAAC Harrier STOVL research aircraft (Ref. 9).

Yaw & Heave Axis Augmentation

Whilst ADS-33 recommends that the level of pitch/roll augmentation be increased from RCAH to ACAH to TRC/PH as the usable cue environment degrades, the constant requirement in the heave and yaw axes is for rate command with height/heading hold (RCHH).

However, there is a problem with achieving a yaw axis rate command response type in a partial authority system. The trim setting on tail rotor collective blade pitch is generally sensitive to airspeed. In a full authority FBW system these trim changes can be accommodated entirely by the AFCS and thus the pedals can be of unique trim configuration, i.e. sprung pedals which when centred correspond to zero yaw rate command. In a partial authority system, where the pedals are linked mechanically to the tail rotor collective, such a unique trim configuration would rapidly result in series actuator saturation. An auto-trim follow-up functionality can be envisaged in which the parallel actuators drive a pedal spring datum to the trim condition. However, pedal force-feel characteristics of partial authority system are typically friction based and thus a hardware change would be required to implement such a system. Thus in both flight and simulation studies additional damping was provided in the yaw axis, with a partial authority heading hold functionality also provided.

The heave axis has not been a focus of the recent PAFCA studies, this axis typically being left unaugmented, however a partial authority height hold functionality was provided in the ground based simulation study described below.

Conduct of Ground Based Simulation Trial

Objectives

The key objectives of the trial conducted on the Advanced Flight Simulator (AFS) at DERA Bedford were as follows:

- To implement, utilising series and parallel actuators, a four axis PAFCA control system for a support rotorcraft.
- To conduct Handling Qualities assessment of PAFCA ACAH and TRC systems in a degraded visual environment and in a turbulent wind condition.

Simulation Configuration

The AFS constitutes the simulation facility in its entirety, including cockpits, visual and motion cueing systems and the over-arching computing environment that hosts the flight dynamics model.

Cockpit : A single-seat cockpit was configured with standard cyclic, collective and pedal controls and representative force-feel characteristics. The collective was friction adjustable with a trim release mechanism. The pedals incorporated a force transducer for ‘feet off’ detection. A TRC select switch, hover-capture switch, and ‘coolie-hat’ beep trim were located on the cyclic stick-top. A TRC disengage could also be initiated by displacing the cyclic stick which automatically defaulted augmentation to ACAH. An EFIS (Electronic Flight Instrumentation System) provided primary flight information via a head-down multi-function display. The EFIS HDD was integrated with the PAFCA control system. On engagement of TRC, height or heading hold, the display would indicate mode engagement. Furthermore, when operating in TRC mode, a groundspeed display was provided on which vectors of both TRC demand and response were shown in a body-referenced earth-axes system.

Visual Cueing : The outside world scene was generated using a Thomson IMAGE 600PT (photo-textured) imaging system, displayed via five collimated CRT monitors, mounted to approximate the field of view from the right-hand seat of a helicopter. The Image visuals featured an airfield database on which cueing for ADS-33 flight test manoeuvres were superimposed. In order to explore DVE operations, the evaluation manoeuvres were flown under simulated night conditions with NightOp night vision goggles (NVGs). Unfortunately time constraints did not permit a full UCE evaluation, but based on previous experience the simulation was estimated to provide UCE=2/3 conditions.

Motion Cueing : Platform motion cues were provided using the Large Motion System (LMS), which is capable of generating significant accelerations, velocities and displacements in pitch, roll, yaw and heave axes, and - depending on the orientation of the cockpit - either surge or sway axes. Sway motion is typically used for helicopter simulations because of the low amplitude surge effects.

Mathematical Model - The DERA HELILINK generic helicopter model was configured to represent a support rotorcraft of similar dimensions the AgustaWestland Merlin. This aircraft model was used to further demonstrate the applicability of the PAFCA approach to a variety of platforms and rotor types. The main rotor model was a disk representation featuring rigid blades, of constant chord and lift slope, with flap spring stiffness located at centre of rotation. A non-uniform inflow model is applied. In addition to the main rotor, separate aerodynamic force and moment contributions from tail rotor, fuselage, fin and horizontal stabiliser are modelled.

Control Law - A PAFCA control law was developed around the HELILINK rotorcraft model in accordance with the design methodology described previously. The series and parallel actuators were modelled with ±10% authority and rate limit respectively. Specific characteristics of the ACAH second order command model and associated closed loop phase limited ADS-33 bandwidth are provided in Table 2.

Axis	**K (deg per stick)**	**ω (rad/s)**	**ζ**	**BW (rad/s)**
Pitch	60	0.89	0.7	1.65
Roll	75	1.28	0.7	2.0

Table 2
ACAH Response Characteristics

Thus the bandwidths in pitch and roll were respectively Level 2 and marginal Level 1/Level2 according to the ADS-33E-PRF specification for “All Other MTEs – UCE > 1”.

The TRC system was tuned to provide a first order response characteristic with a rise time of 4.6 seconds, which accords with the ADS-33 requirement of between 2.5 and 5 seconds. However, for reasons described previously, the demand generated by trim switch displacement was for an acceleration of 5kn/s^2.

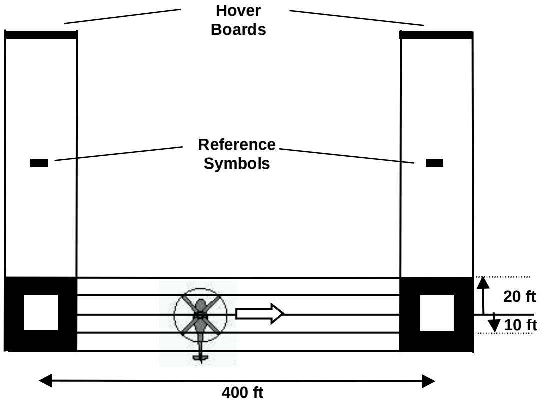
Evaluation Manoeuvres

The configurations were evaluated in two flight test manoeuvres selected from ADS-33E-PRF, these being the lateral reposition and the hover.

The objectives of the lateral reposition manoeuvre are as follows:

- Check roll axis and heave axis handling qualities during moderately aggressive manoeuvring.
- Check for undesirable coupling between the roll controller and the other axes.

A lateral acceleration from hover to approximately 35 knots groundspeed is initiated. Subsequently the rotorcraft is decelerated and repositioned laterally in a stabilised hover 400 ft down the course. The performance requirements and task layout are as shown in Figure 5.



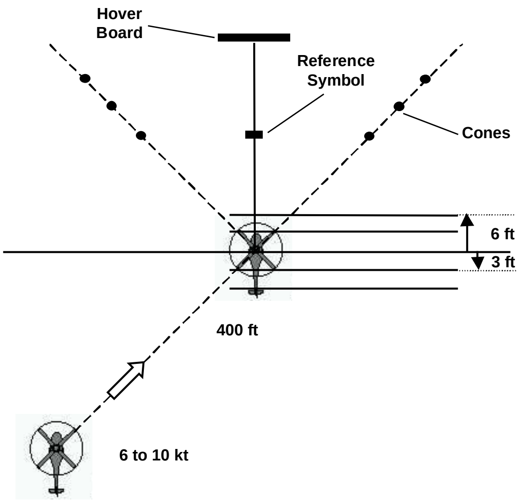
PERFORMANCE METRIC	**CRITERIA**	
	GVE	**DVE**
Longitudinal track - ±X ft	10 (20)	10 (20)
Altitude - ±X ft	10 (15)	10 (15)
Heading ±X deg	10 (15)	10 (15)
Manoeuvre time (s)	18 (22)	20 (25)

Figure 5
ADS-33E-PRF Layout and Cargo/Utility Performance Requirements for Lateral Reposition

The objectives of the hover manoeuvre are as follows:

- Check ability to transition from translating flight to a stabilised hover with precision and a reasonable amount of aggressiveness.
- Check ability to maintain precise position, heading, and altitude.

The performance requirements and task layout for the hover manoeuvre are shown in Figure 6. The manoeuvre is initiated at a ground speed between 6 and 10 knots, at an altitude less than 20 ft. A target hover point is oriented at 45 degrees relative to the heading of the rotorcraft. The target hover point is a repeatable, ground-referenced point from which rotorcraft deviations are measured. The ground track is such that the rotorcraft arrives over the target hover point. It is specified that the transition to hover should be accomplished in one smooth manoeuvre.



PERFORMANCE METRIC	CRITERIA	
	GVE	DVE
Stabilise hover within X seconds	5 (8)	10 (20)
Stabilised hover duration	30 (30)	30 (30)
Longitudinal/lateral position - ±X ft	3 (6)	3 (6)
Altitude - ±X ft	2 (4)	2 (4)
Heading ±X deg	10 (10)	10 (10)
No objectionable oscillations	✔ (-)	✔ (-)

Figure 6
ADS-33-PRF Task Layout and Cargo/Utility Performance Requirements for Hover

A moderate tailwind, of 20kn mean speed, was introduced to the tasks to explore the impact of a disturbance environment on the PAFCA concepts. A statistical discrete gust model of turbulence was also introduced at a moderate intensity (RMS = 3.4 kn).

Evaluation Methodology

The Cooper Harper handling qualities evaluation approach (Ref. 1) and questionnaire were utilised. Prior to awarding subjective ratings the pilot would complete the manoeuvre several times until a consistent strategy and task performance level were achieved. The pilot would then perform the manoeuvre two more times, these being the runs for which both subjective and objective data would be recorded.

Although the majority of spatial task performance criteria were described by the task specific ground markings, it was recognised that the degraded visual conditions would make it difficult for the pilot to assess performance. In order to provide rapid and accurate feedback, a software element was generated to calculate performance at the end of each task. The software was also configured to identify stable end conditions thus removing the variability associated with subjective perception of a hover state.

Unfortunately a number of constraints meant that only two pilots participated in the evaluations and for several test points only one pilot evaluation was captured. Thus the following subjective results cannot be presented as conclusive evidence, but should instead be considered indicative of the potential of the system. It is recognised that a comprehensive handling qualities evaluation would be required to assess fully the concepts.

For both ACAH and TRC/TAC configurations, the pilots were briefed to make use of the height and heading holds wherever appropriate. When using TRC/TAC the pilots were guided to investigate strategies combining both response types.

Results of Ground Based Simulation Trial

Lateral Reposition

Figure 7 shows the HQRs captured in the lateral reposition manoeuvre.

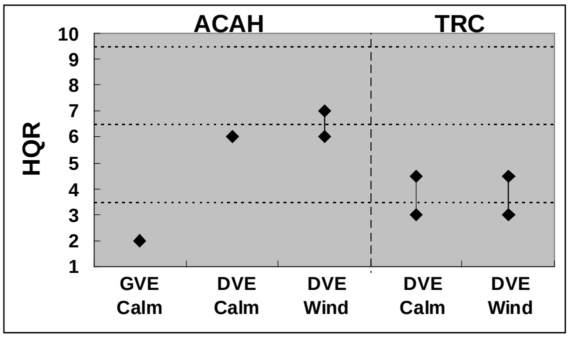


Figure 7
Subjective Ratings for Lateral Reposition

An evaluation of the ACAH configuration was conducted in calm GVE conditions as a baseline and yielded desired task performance with low workload. During the transition saturation was noticeable in both pitch and roll axes but the required compensatory activity was considered to be low and predictable. However, when conducted in the DVE, where the pilots ability to perceive deviations in attitude and position is reduced, the compensation required to inhibit the coupled response in saturation was less timely resulting in extensive workload required to stabilise out of the transition. The presence of the turbulent wind heightened these issues with the ratings becoming borderline Level 2/3.

A GVE evaluation was not conducted for the TRC/TAC mode since the ACAH configuration with its higher inherent agility would be selected where good visual cueing was available. In the DVE the pilots opted to use the TRC/TAC response throughout the entire manoeuvre with an engagement of Hover Hold in the final phase. However, both pilots commented that predictability was an issue with respect to judging how far in advance of the endpoint the hover hold should be engaged. The addition of wind and turbulence was not noticeable to the pilots when using TRC/TAC.

Figure 8 shows a comparison of time histories of control activity and response characteristics from an example of each configuration performing the manoeuvre in the DVE and wind. The vertical line on each plot denotes the completion of the manoeuvre. The roll attitude and lateral speeds used are similar indicating comparable aggression. However, the times taken were marginally adequate for the ACAH configuration and marginally desired for TRC/TAC. The difference is due to the additional time required to stabilise the ACAH configuration after saturation in the deceleration phase. The series actuators in TRC/TAC system remained unsaturated with the benefit of providing a virtually decoupled response, evidence of which is provided by the superior longitudinal task performance.

Whilst the cyclic stick was not used in TRC/TAC mode, comparison is provided to show the low activity associated with the parallel actuator auto-trim follow-up, an aspect that attracted favourable comment. Although not shown, heading and height were maintained within desired bounds throughout the manoeuvre, demonstrating satisfactory hold functionality.

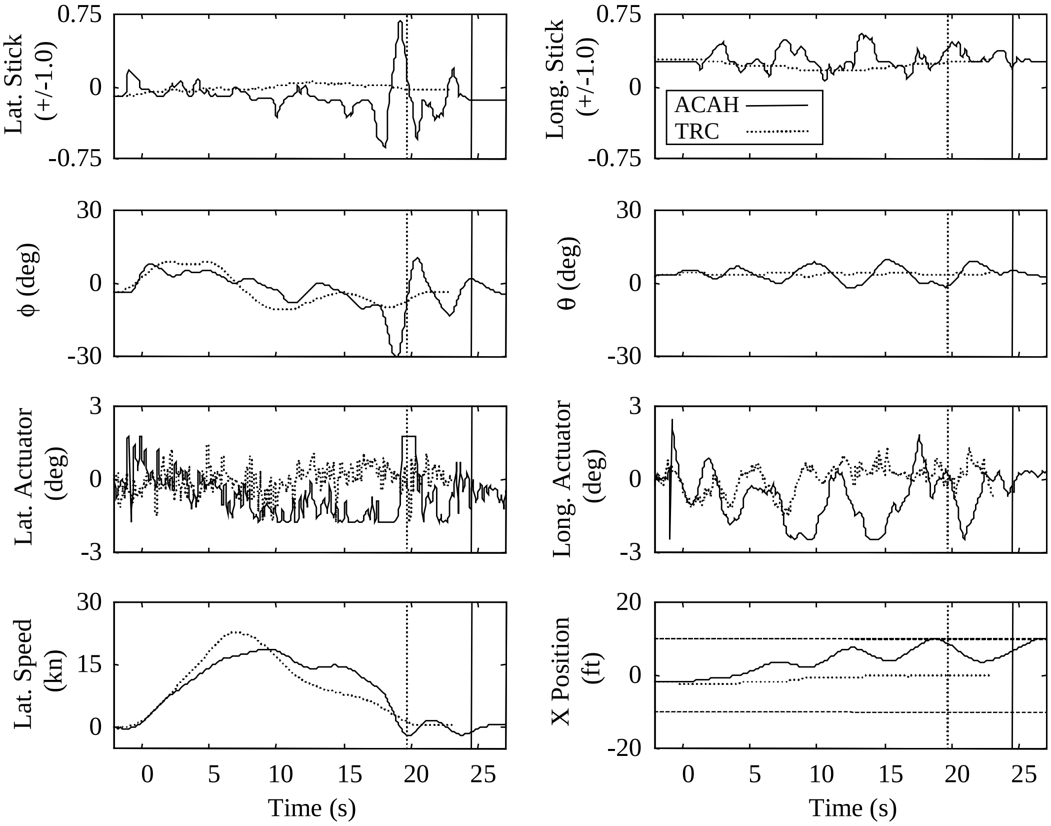


Figure 8
Control Activity and Task Performance in Lateral Reposition

Hover

Figure 9 shows the HQRs captured in the hover manoeuvre.

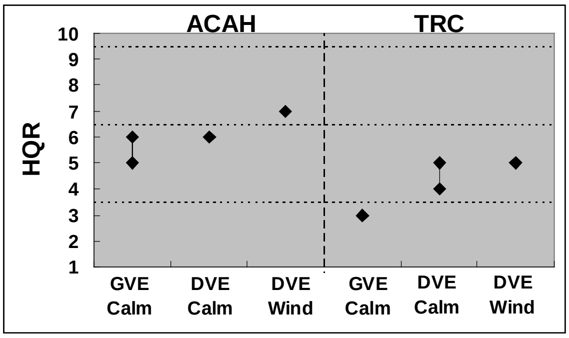


Figure 9
Subjective Ratings for Hover

The GVE baseline assessment of the ACAH configuration produced Level 2 ratings, this being due to inceptor force-feel problems associated with trimming the stick to a neutral attitude/zero force condition in the hover. In the DVE case, the reduced field of view associated with the NVGs required the pilot to turn his head repeatedly over a 90 degree in order to detect positional drift. This additional workload became intolerable when the attitudes were perturbed by a turbulent wind, conditions under which adequate task performance could no longer be achieved.

The two pilots adopted differing strategies when presented with the TRC configuration. Because of the four-way nature of the trim switch, it was difficult to set up a diagonal flightpath that would intersect the hover box. Similarly, when an appropriate flight path had been achieved these same ergonomic deficiencies prevented a smooth diagonal deceleration profile. Thus one pilot opted to fly the transient component of the manoeuvre in ACAH engaging the hover capture facility only when on position – a strategy that produced the Level 1 rating in the GVE. The other pilot used TRC/TAC for translation and hover capture for deceleration.

Desired performance was achievable in the DVE with the TRC/TAC system, but required accurate prediction of the small translations associated with automatic deceleration to the final hover point. Where the initial prediction of terminal position was wrong, the response characteristics of the TRC/TAC system were not appropriate for rapid repositioning. Consequently the task performance was not sufficiently consistent to warrant Level 1 ratings. Once again the impact of wind on the TRC/TAC system was relatively transparent in terms of workload, but was responsible for a small degradation in positional performance.

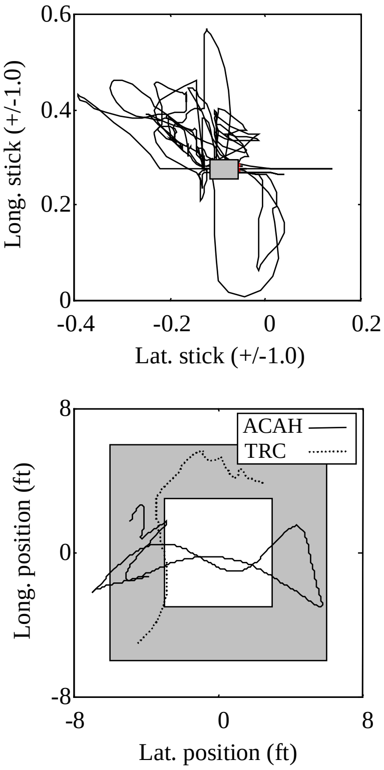


Figure 10
Control Activity and Task performance in Hover

Figure 10 shows a comparison of the control activity and positional task performance associated with ACAH and TRC/TAC in the 30 second hover phase of the task. The cases shown were both conducted in the DVE with a turbulent wind.

The pilot did not achieve desired performance, denoted by the central white square, in either configuration and made an excursion outside of adequate for the ACAH response type. However, the control cross-plot shows that significant workload was associated with the maintenance of a stable hover in the ACAH configuration. In comparison, the workload associated with TRC/TAC for this phase was zero, since the pilot made no inputs. In order to show the low magnitude of TRC/TAC parallel actuator activity, the region encompassing the back-driven stick position is highlighted as a grey rectangle.

Conclusions

Key conclusions from the ground-based simulation study are as follows:

- A TRC/TAC response type can be implemented within the actuation limitations typical of extant AFCS hardware and has the potential to provide significant enhancement of mission effectiveness in degraded environmental conditions.

- Auto-trim follow-up, implemented through the parallel actuators, can prevent series actuator saturation for moderately aggressive manoeuvring in TRC/TAC mode. The associated inceptor activity is non-intrusive and a moderate turbulence level can be tolerated without significant performance degradation.
- The transition between partial authority TRC/TAC and ACAH response types can be managed with no adverse transient behaviour

The implementation of a TRC/TAC system of the kind investigated could be improved in the following ways:

- Improved responsiveness could be conferred by transition to a higher bandwidth, non-frequency matched, inner loop attitude command system on TRC/TAC engage.
- An enhanced trim switch could be introduced providing an analogue multi-directional command functionality.

Conduct of In-Flight Simulation Trial

Objectives

An in-flight investigation of a subset of PAFCA concepts was conducted on the NRC Bell 205 Airborne Simulator. The primary objectives were to implement and flight test the following partial authority configurations:

- An ACAH response type designed using the frequency matching approach.
- A TRC response type controlled via a stick-top trim switch.

NRC Bell 205 Airborne Simulator

The Bell 205A (Figure 11), acquired by the NRC in 1969, has a teetering two blade main rotor, is powered by a Lycoming T53-13B engine and has a maximum take-off weight of 9500 lbs. The main rotor stabilization bar and associated hardware has been removed and the horizontal elevator has been fixed. The helicopter has been developed into an Airborne Flight Simulator, using an in-house design and the installation of flight control equipment.

The evaluation pilot, when engaged by the safety pilot, has control of the aircraft through a single string, fully programmable, full authority fly-by-wire (FBW) control system. To provide this capability, the standard Bell 205A aircraft actuators were replaced with specially designed dual-mode electro-hydraulic actuators, which can be controlled either mechanically by the safety pilot or electrically by the evaluation pilot.

Figure 11
NRC Bell 205 Airborne Simulator

The open architecture of the FBW computing system allows the engineer to ‘drop’ controller code in place easily. In the study described the code was generated automatically from controller module of a DERA HELILINK simulation model, using the Matlab Real-Time Workshop, making the interface between desktop design and aircraft highly efficient.

Mathematical model

It was recognised that a successful application of the frequency-matching approach would require a flight mechanics model of relatively high validity. To this end, the DERA HELILINK model was configured with Bell 205 parametric data and underwent a limited optimisation against hover flight data captured in open loop testing of the NRC aircraft.

A comparison of the frequency domain characteristics of the model and aircraft in the hover is shown in Figure 12. An accurate representation of both gain and phase was achieved up to approximately 5 rad/s where the aircraft gain response falls off more rapidly than that predicted theoretically.

This level of model validity was considered sufficient for the experimental study. However, should the design approach be applied as an AFCS upgrade in the future, improved system identification and validation would be recommended. The more rigorous approach to modelling promoted in Ref. 10 in which comprehensive flight test and formal system identification methods are applied, would be highly appropriate.

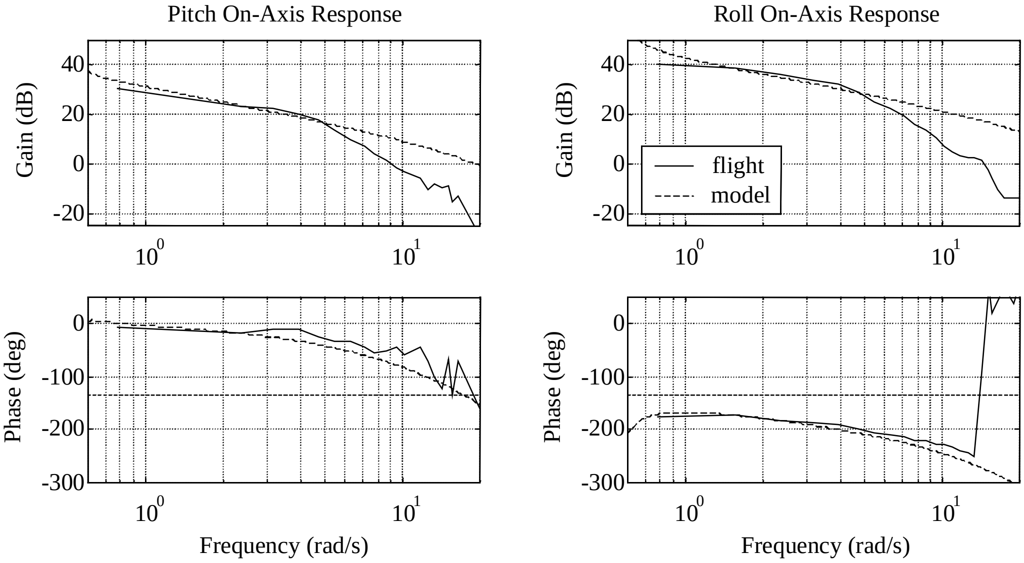


Figure 12
Flight Mechanics Model Validity in Frequency Domain

PAFCA Control Law Design

Since the experimental component of the aircraft flight control system features a full-authority FBW system, the hardware attributes of a conventional PFCS were simulated in software.

It was considered inappropriate to revert to the unstabilised dynamics of the Bell-205 on saturation of the modelled actuator limits since the open loop dynamics associated with the teetering rotor design result in attitude bandwidths much lower than those of most modern in-service types.

It was therefore decided that a full-authority inner loop controller providing additional rate damping would be used to emulate more representative open-loop dynamics. Figure 13 shows a conceptual representation of the full system.

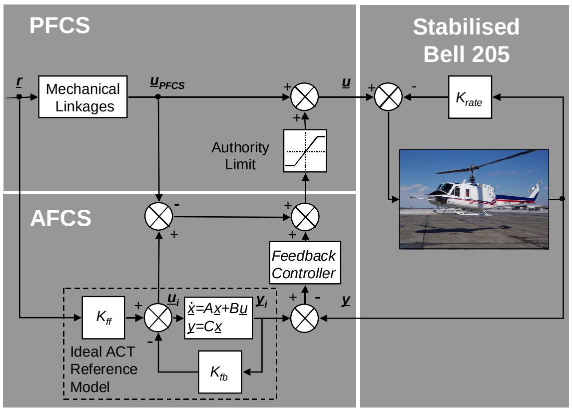


Figure 13
PAFCA Controller Architecture for NRC Bell-205

The full-authority rate stabilised inner loop system had phase limited attitude bandwidths of 1 rad/s and 2 rad/s in pitch and roll respectively. It was to the frequency domain characteristics of this system that the frequency matching of the PAFCA closed loop system was conducted.

In common with the approach described in the simulation study, the attitude control powers were prescribed first and the frequency and damping of the second order command model then submitted as variables in an optimisation of the closed loop frequency response against ‘open loop’ data. Table 3 contains the resulting optimum dynamics and associated design bandwidths.

Axis	**K (deg per stick)**	**ω (rad/s)**	**ζ**	**BW (rad/s)**
Pitch	45	0.85	0.73	1.40
Roll	60	1.54	1.23	2.80

Table 3
ACAH Design Response Characteristics

The control law was then implemented on the aircraft and frequency sweeps conducted to establish how successful a match had been achieved. The resulting closed loop frequency domain characteristics are shown, compared with those of the pseudo open loop system, in Figure 14. A close match can be seen in both gain and phase across the intended 1-10 rad/s bandwidth. Furthermore the measured pitch and roll bandwidths were close to their design values, being 1.25 rad/s and 2.88 rad/s respectively.

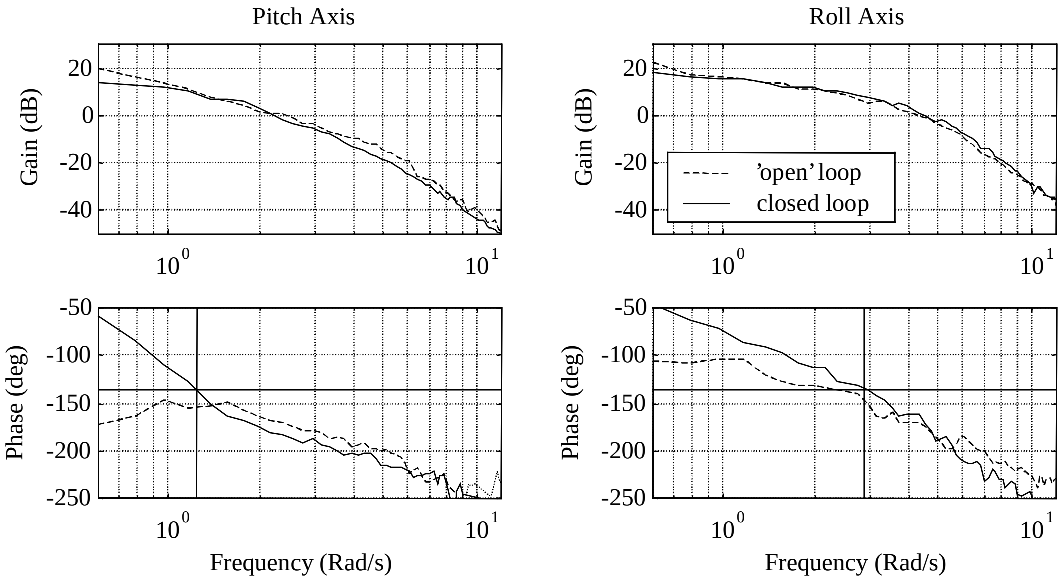


Figure 14

Frequency Domain Characteristics of Pseudo Open Loop and Closed Loop Systems

ACAH Flight Test Results

In order to assess the handling characteristics of the partial authority control system a number of ADS-33 manoeuvres were flown in good visual conditions. In addition to a full authority baseline, a range of series actuator authorities was considered to explore the nature of saturation.

The lateral cyclic activity, roll attitude and lateral series actuator activity associated with an side-step manoeuvre, for a ±15% authority case, are shown in Figure 15.

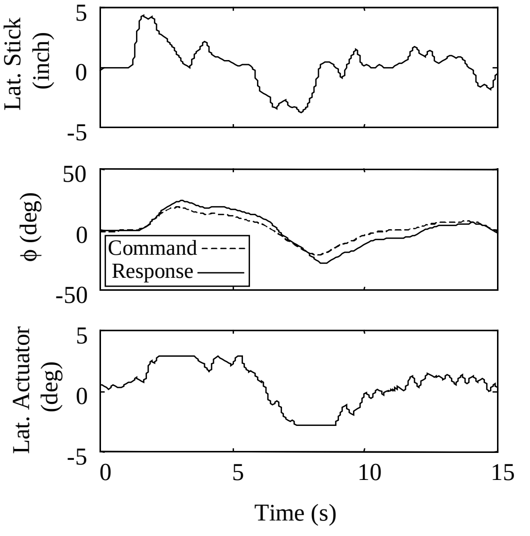


Figure 15

Flight Test of ±15% Authority ACAH System - Side Step Manoeuvre

The manoeuvre was relatively aggressive with 25 degree attitudes being achieved in both the roll-in and reversal and the series actuators remained saturated for 2-3 seconds in each instance. Observing the relationship between stick and idealised model output, it is clear that the desired attitude response characteristic was commanded. Prior to saturation the aircraft response followed the model closely indicating an appropriate feedback design. On saturation the attitude started to deviate from the model and, to arrest its growth, the pilot applied a small corrective input. Despite this visible compensation the pilot awarded an HQR of 3, commenting that saturation was not evident and that the roll response felt ‘crisp’. Conversely, when the same manoeuvre was flown with full authority augmentation, the response was considered to be too sluggish and the HQR worsened to 4.5. In validation of the previous NRC and DERA/AFDD studies (Ref. 3,4,5), the additional responsiveness associated with the transition to the unaugmented open-loop dynamics, provided increased agility at high aggression.

The longitudinal cyclic activity, pitch attitude and longitudinal series actuator activity associated with an acceleration-deceleration manoeuvre, also for a ±15% authority case, are shown in Figure 16. The aggression levels are moderately high, with pitch attitude deviations from trim of the order 20-25 degrees, and saturation is encountered over a 7-8 second period following the reversal. Once again the feed-forward command generator and feedback controller confer a clear attitude response type during the initial, unsaturated, acceleration. Despite saturation the pilot, did not observe any transient behaviour, reported a ‘solid’ ACAH characteristic and awarded an HQR of 2.

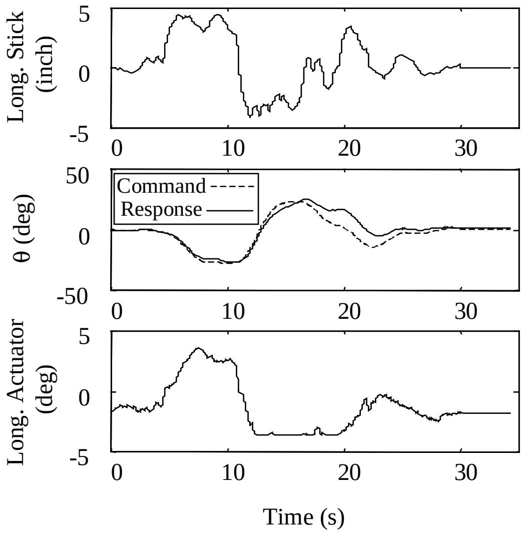


Figure 16
Flight Test of ±15% Authority ACAH System - Acceleration Deceleration Manoeuvre

Since the target attitude had not been reached at the point of saturation the initial transition between systems can be seen as a slight reduction in pitch rate. This initial slugging of the response upon saturation provides some explanation as to why, when compared with full authority implementation, an agility benefit paralleling that seen in the roll axis was not perceived. Although with the full authority case the HQR worsened by one point, the responsiveness in both full and partial authority implementations was considered to be appropriate for the manoeuvre.

The same manoeuvres were also flown with a ±10% authority implementation. The impact on the acceleration-deceleration manoeuvre was fairly minimal, the HQR degrading by one point but remaining Level 1. However, during the side step, increased saturation was encountered in both axes and the resulting coupled behaviour degraded the HQR to 4.5 (Level 2).

The ±10% authority configuration was also flown, in a number of manoeuvres, in a simulated DVE. The evaluation pilot was provided with the NiteOp NVGs with daylight filters, allowing the safety pilot to operate in GVE conditions. The assessment was only very brief, but similar pilot comment to the GVE evaluation was received in terms of task performance, albeit with slightly increased workload.

TRC Flight Test Results

An initial implementation of a partial authority TRC response type was also investigated during the trial. In common with the simulation study the system was configured to respond to trim switch inputs. However, since an integrated display was not available, TAC was not an option and only the “on-off” TRC response was implemented. The command model was configured to provide a first order like response with a time constant of 5 seconds. The amplitude of response was limited to 7.5kn to avoid significant attitude perturbation. Parallel actuator auto-trim follow-up functionality, akin to that used in simulation, could not be provided and hence a ±15% series actuator authority was emulated. Groundspeed feedback was provided via complementary filtering of Doppler and integrated accelerometer measurements.

Figure 17 shows time histories of the input, idealised model command and measured groundspeed for longitudinal and lateral inputs. Series actuator activity is also shown with the uper and lower boundaries of the ±15% authority shown for comparison.

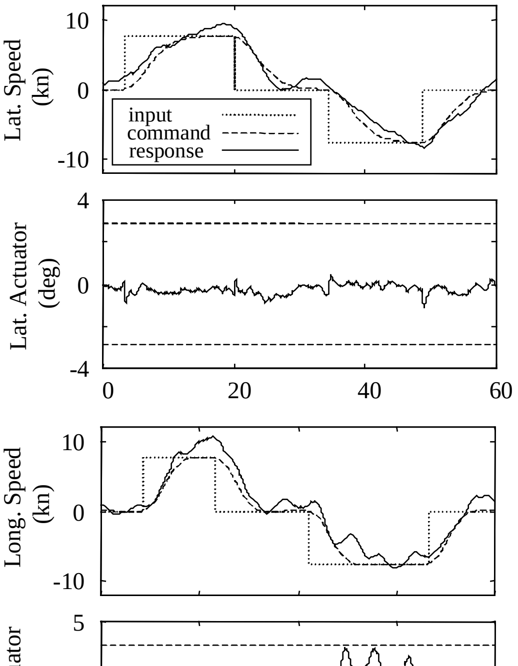


Figure 17
Flight Test of ±15% Authority TRC System

In both axes the aircraft speed can be seen to have followed the command model, albeit somewhat coarsely. There was a tendency to overshoot the target speed and a 2-3 degree pitch nod was induced which resulted in a slightly oscillatory longitudinal speed. At the low levels of manoeuvre aggression associated with this TRC implementation, saturation did not occur in either axis.

The longitudinal speed response required significantly more actuator activity primarily to overcome the higher inertia of the fuselage longitudinally. Importantly no high frequency, large amplitude actuation requirements were evident and thus an auto-trim follow-up, such as that used in simulation, could be expected to further reduce the proximity of the series actuator to their limits.

It is difficult to identify whether the cause of these performance issues was instrumentation or control law based, but clearly some additional work would be required to provide a system that could be fielded operationally. Nevertheless the concept of a trim switch TRC control system was demonstrated successfully in a partial authority context.

Conclusions

Key conclusions from the in-flight simulation study are as follows :

- The PAFCA architecture has been demonstrated to provide a robust and flexible framework for successful implementation of limited authority ACAH and TRC response types.
- The concept of frequency matching was proven to be viable in the presence of real-world uncertainty but could be improved with comprehensive approach to modelling using flight test and system identification.
- A ±15% series actuator authority limit delivers significantly improved performance over a ±10% limit for an ACAH system, but a ±10% limit with auto-trim follow-up should be sufficient for a TRC system.

Summary

This paper has described a series of ground-based and in-flight simulation experiments exploring the implementation issues and benefits arising from application of limited authority attitude command and translational rate response types for operations in degraded visual conditions. It has been demonstrated that there is significant potential for affordable AFCS upgrades for current generation helicopters that will deliver substantial flight safety and mission effectiveness benefits.

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