Handling Qualities Degradation in Tilt-Rotor Aircraft Following Flight Control System Failures

Neil Cameron
Research Associate
Flight Science & Technology
University of Liverpool

Gareth D Padfield
Professor of Aerospace Engineering
Flight Science & Technology
University of Liverpool

Abstract

Handling Qualities are critical in terms of performance and flight safety and will have a strong influence on the design of a future Civil Tilt-Rotor. As with all civil aircraft, the design must comply with civil aviation airworthiness regulations within which safety standards play a major role, thus any handling qualities degradations caused by a flight control system component failure must be quantified through a safety analysis. This paper presents the steps taken to determine failure severity for different types of component failure such as a loss, malfunction or degradation, focusing on the results from a series of piloted simulation trials, with the FLIGHTLAB XV-15 tilt-rotor model, held at the University of Liverpool for the European 5th Framework ACT-TILT project. Degraded failure results are presented for several mission tasks in aeroplane, conversion and helicopter modes and an aircraft maximum tolerable actuation rate limit recommended, followed by a malfunction failure analysis which determines the maximum tolerable hard-over position and 'passivation' time for each function. Work in the ACT-TILT project focuses on the AGUSTA-WESTLAND ERICA tilt-wing/tilt-rotor design concept and as such also considers the affect of a tilt-wing failure and the possibility of using helicopter controls in the event of a control function failure in aeroplane mode.

Introduction

The European 5th Framework project ACT-TILT (Active Control Technology for TILT-rotor aircraft) aims to define the Flight Control System (FCS) in order to improve safety, reliability and affordability of a European civil tilt rotor CTR aircraft. A CTR will be designed to possess excellent HQs throughout its operational flight envelope (OFE) and good handling qualities throughout its Service Flight Envelope (SFE). In addition, any HQs degradation caused by failure of FCS components or loss of functions will be quantified via a safety analysis.

One aspect of The University of Liverpool's (UoL's) contribution to the ACT-TILT project is to provide, via analysis supported by an extensive range of piloted simulation, the information required to undertake a flight control system failure hazard analysis. This paper begins with an introduction to tilt-rotor flight control and continues with a failure analysis discussion, including failure type and classification. The mission task elements (MTEs) used in the simulation trials at UoL are then presented in conjunction with the findings from the trials, for the degraded mode failures.

A 'degradation' of particular importance is when an actuation system failure occurs resulting in a reduction in the maximum actuation rate available at the control surface. One aspect of the research has therefore focused on defining a maximum tolerable rate limit, in the sense that handling qualities remain within the Level 2 (acceptable) range. Other important aspects under study include the impact of failure transients, following a 'malfunction', and particularly a tilt-wing actuation 'loss'. The potential for using helicopter mode controls in the event of an aeroplane control surface actuation failure is also examined.

Tilt-Rotor Control

Tilt-rotor aircraft are designed to take-off and land vertically as a helicopter (nacelles at 90^o) and cruise as a fixed wing aeroplane by tilting the nacelles forwards to 0^o. The transformation phase is thus known as the conversion and flight with nacelles fixed at intermediate settings is described as the conversion mode.

The take-off and landing phases are performed in helicopter mode using the helicopter controls, where longitudinal stick inputs control aircraft pitch via combined longitudinal cyclic blade pitch, lateral stick inputs control roll using differential collective blade pitch and heave control is implemented through collective blade pitch. Finally, yaw is controlled via differential longitudinal cyclic blade pitch using pedal inputs. Likewise, aeroplane mode is flown using conventional fixed wing controls, longitudinal stick controls elevator and pitch, lateral stick controls ailerons and roll and finally yaw is controlled through use of pedals and rudder while collective controls rotor thrust. The aeroplane mode controls remain operational during all flight conditions, from hover through conversion mode and, of course, aeroplane mode. The helicopter controls, however, are only fully functional in helicopter mode. When the pilot begins conversion to aeroplane mode, the helicopter controls are phased out as a function of nacelle angle.

The tilt-rotor flight control system must provide adequate control in all three of the flight modes and a smooth blending between them. This requirement renders its design more complex than that of a helicopter, due to the combination of control surfaces and actuators required as illustrated in Figure 1.

A tilt-rotor requires three actuators for each rotor, one for collective and differential collective blade pitch, one for longitudinal and differential longitudinal cyclic blade pitch and although no control is applied through lateral cyclic blade pitch, an actuator is still required to control blade flapping. Two more actuators are required for converting to aeroplane mode, one for each nacelle and a further two for each aeroplane control surface - flaperons, high lift flaperons, elevator and rudder. Finally, the ERICA tilt-rotor model (ref 1) under consideration in ACT-TILT, has a unique tilting wing, which requires a further two actuators.

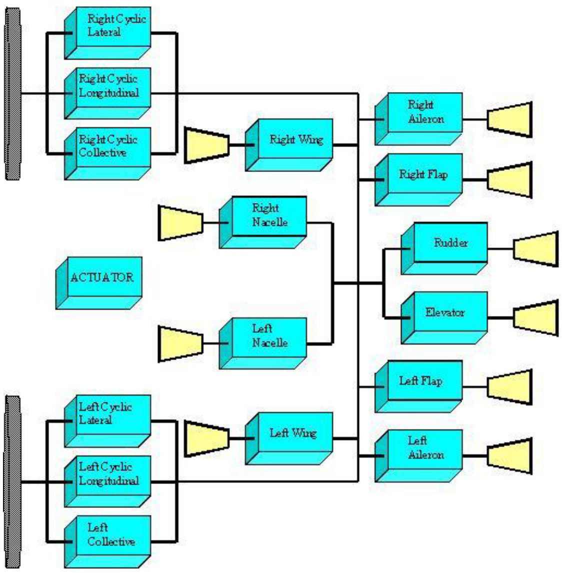


Figure 1 Tilt-Rotor/Wing Actuator Schematic

<u>Function Failure</u>

The pilot must be able to maintain adequate control of the aircraft following any failure and any failure transients must also be manageable by the system or pilot. Therefore it is vital to ensure that the affects of control function failures are assessed early in the design to establish severity levels and reliability requirements.

ADS-33 (ref 2) proposed that if one or more failure states exist, a handling qualities degradation is permitted, which is assessed by relating the tolerable handling qualities degradation to the probability of encountering a failure, however this is permitted only if the probability of encountering the failure is sufficiently small. This ADS-33 proposed format forms the basis of the failure analysis presented here, which began with tabulating all rotorcraft failure states, where three failure types were envisaged:

- Loss of function – A loss is a frozen value or a default status (the control surface does not respond to the corresponding control input),
- Malfunction – The control surface deflection is not frozen as in a loss, but does not move consistently with the input (e.g. hard-over, slow-over or oscillations),
- Degradation of function – The function is still working but with degraded performance (e.g. low voltage power supply or reduced hydraulic pressure).

The next step was to make an initial estimation of the affect of the failure and to classify the failure probability in terms of flying hours as demonstrated by Table 1. This must be applied to each control function for each failure type in all three modes where for example, the probability of a minor failure occurring is once every thousand (10^3) flying hours (ref 3) while the probability of a catastrophic failure occurring is defined as once in a billion (10^9) flying hours.

Table 1 Failure Classification Table

Failure-Severity	Maximum Probability of Occurrence / Flight Hour	Failure Condition Effect
Catastrophic	Extremely Improbable < 10^{-9}	All failure conditions that prevent continued safe flight and landing.
Hazardous	Extremely Remote < 10^{-7}	Large reduction in safety margins or functional capabilities. Higher workload or physical distress such that the crew could not be relied upon to perform tasks accurately or completely. Adverse effects upon occupants
Major	Remote <10^{-5}	Significant reductions on safety margins or functional capabilities. Significant increases in crew workload or in conditions impairing crew efficiency. Some discomfort to occupants.
Minor	Probable < 10^{-3}	Slight reduction in safety margins. Slight increases in crewworkload. Some inconvenience to occupants.

Critical failures can thus be identified and separated from the less critical failures allowing the engineer to focus on these critical failures, for example it is not crucial to examine the affect of tilt-wing loss in helicopter mode, except to the extent that conversion to aeroplane mode is then not permissible). The following section focuses on degraded failures while loss and malfunction failures are reported later.

Degraded Failures

A failure in the hydraulic system will result in a reduced hydraulic pressure being supplied to the actuator, degrading its performance, such that the actuator can only operate at a reduced rate. If this does occur a loss of mission may result, however enough control authority should remain to allow diversion and landing, thus from the Failure Hazard Analysis table presented, all degraded modes are required to be classified as having no worse than a major affect. Therefore in the event of a degraded failure the tilt-rotor must remain operational, albeit with poorer handling qualities. As a result, it is essential to determine the reduced actuation rate that confers no worse than Level 2 HQs in the event of a failure.

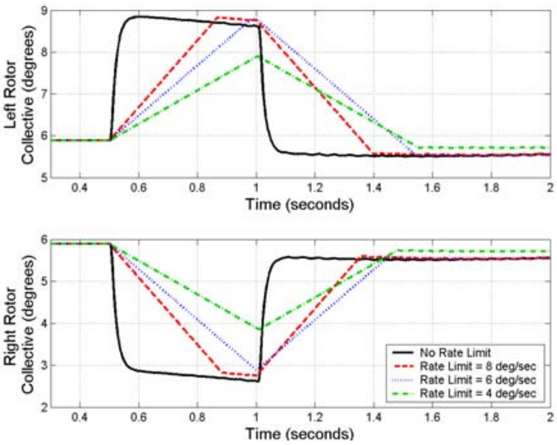


Figure 2 Collective Response to 0.5 sec Step Input in Lateral Stick for Varying Rate Limits

The ‘no rate limit’ case in Figure 2 demonstrates differential collective pitch response to a 50% lateral stick step input applied for 0.5 seconds in hover with the stability and control augmentation system (SCAS) switched off. Figure 2 also shows blade collective pitch angle change to the same response with a reduced actuation rate. If for example, a rate limit of 6^{o}/sec is applied, it takes 0.5 seconds to reach the commanded input when the input is disengaged almost immediately taking the same time to return to its trim position. If rate limiting is increased further as demonstrated by the 4^{o}/sec case, the commanded blade deflection is not reached before the input is disengaged.

The primary means of assessing the perceived helicopter handling qualities in the present exercise is through piloted simulation where the task HQs are graded using the Cooper-Harper rating scale (ref 4). However, an initial handling qualities assessment can be made offline using the attitude quickness criteria (ref 2), which will help to identify the rate limit associated with Level 2/3 HQs boundary, thus reducing the number of test points required in the simulation trial.

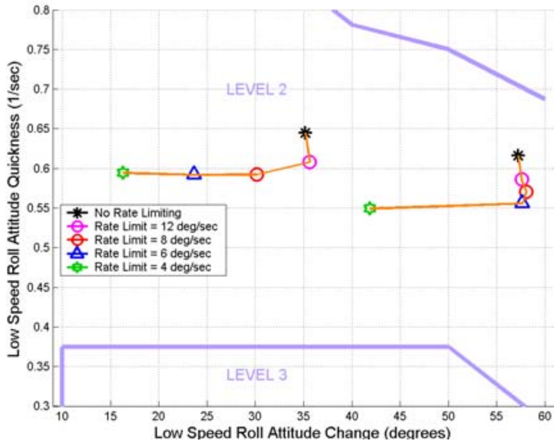


Figure 3 Roll Attitude Quickness

Figure 3 shows the roll attitude quickness resulting from lateral stick inputs ranging from 0.3 to 0.5 seconds. As differential collective rate limiting increases in each case, the attitude quickness decreases, thus, in this case, 6^{o}/sec is approximately the lowest actuation rate for this control input that allows the commanded attitude change. If the rate limit is further decreased to 4^{o}/sec, the commanded control surface displacement is not reached before the input is disengaged, thus the attitude change is significantly reduced. Clearly, if the control input is applied for a shorter period of time such as 0.3 seconds, the minimum rate limit that generates the commanded attitude change increases to approximately 12^{o}/sec.

It can be concluded from Figure 2 and Figure 3 that as collective/differential collective rate limiting is increased, the HQs degrade towards the level 2/3 boundary as expected, however longer control inputs are required to generate the roll attitude quickness for a prescribed attitude change at the Level 2/3 boundary.

Handling Qualities for Tilt-Rotor Aircraft Trials

To determine the minimum tolerable actuation rate of each actuator and the Level 2/3 HQs boundary, a series of piloted simulation trials were conducted at UoL, with test pilots and engineers from CAA, DGA, ex-Royal Navy (currently British Airways pilot), NLR, DLR, ONERA and Eurocopter participating. In all, four test pilots took part in three simulation trials, each flying a range of specified mission task elements, and will be referred to as pilot A, B, C and D respectively for the remainder of the paper.

Although the ACT-TILT project focuses on the AGUSTA-WESTLAND ERICA configuration (ref 1), this configuration was still under development at the time of the trials, thus the FLIGHTLAB XV-15 simulation model (ref 5) was used.

The test pilots were required to fly a range of nominally, single axis MTEs specifically devised to assess axial performance in helicopter, conversion or aeroplane modes. At the end of each task, the pilots completed an in-cockpit questionnaire, which not only provided the engineers with an insight into the vehicle response and limits, but also aided the pilot in returning an HQR using the Cooper-Harper handling qualities rating (HQR) scale (ref 4). The actuator rate limit was varied and the process repeated until the Level 2/3 boundary was breached when an HQR of 7 or higher was returned.

<u>The University of Liverpool Flight Simulation Laboratory</u>

Figure 4 The University of Liverpool 'HELIFLIGHT' Flight Simulator & Cockpit View

HELIFLIGHT is a PC-based re-configurable flight simulator developed with five key components that are combined to produce a relatively high-fidelity system (ref 6), including:

- Selective fidelity, aircraft-specific, inter-changeable flight dynamics modelling software (FLIGHTLAB) with a real time interface,
- 6 degree of freedom motion platform,
- Four axis dynamic control loading,
- A three channel collimated visual display for forward view, plus two flat panel chin windows, providing a wide field of view visual system,
- Computer-generated instrument panel and head up displays (reconfigurable).

The software at the centre of operation of the facility is FLIGHTLAB, providing a modular approach to developing flight dynamics models and enabling the user to develop a complete vehicle system from a library of predefined components. The flight dynamics models form a vital part of a flight simulator, the detail of which will ultimately define the fidelity level of the simulation.

Of equal importance is the environment into which a pilot is immersed. Three collimated visual displays are used to provide infinity optics for enhanced depth perception, which is particularly important for hovering and low speed flying tasks. The displays provide 135° horizontal by 40° vertical field of view which is extended to 60° vertical field of view using two flat screen displays in the chin windows.

The sensation of motion is generated using a six-axis Maxcue platform, which is electrically actuated. To maximize the usable motion envelope, the drive algorithms feature conventional washout filters that return the simulator to its neutral position at acceleration rates below the perception thresholds.

<u>Mission Task Performance Criteria & Results</u>

A series of predefined Mission Task Elements (MTEs) such as the roll-step, bob-up, heave-hop and acceleration-deceleration task were flown in the trials. These tasks are presented in the following sections followed by the trial results.

<u>Roll-Step</u>

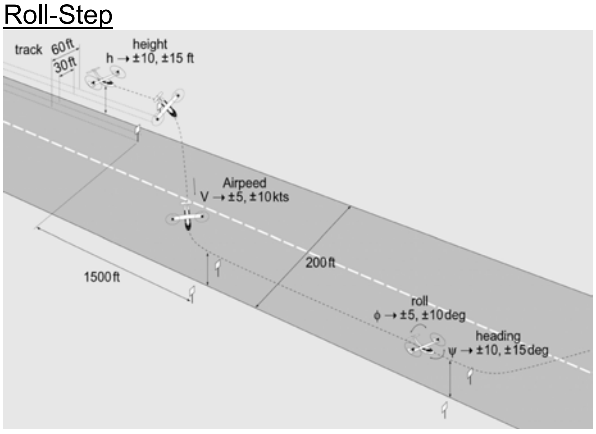


Figure 5 Roll-Step Task

The roll-step (ref 7) depicted in Figure 5 is flown along a runway 200ft wide flanked by a series of gates 500ft apart, where the pilot is required to fly through an ordered series of these gates depending on flight mode and speed which define the roll-step task. The pilot is required to align with the runway left edge, flying at a reference height and speed, then on reaching the specified starting gate, initiate the task by rolling to the right across the runway and realign on the right runway edge upon reaching a specified gate. The second phase of the task involves a reversal of this process, i.e. on reaching the specified gate, initiate a turn to the left to roll back across the runway to the next specified gate. Finally a stabilisation period of 1000ft is included.

When passing through the specified gates, the pilot must meet a set of performance criteria, which do not vary with aircraft mode or speed. Figure 5 illustrates these constrains where the roll angle is $\pm 5/10^{o}$ for desired/adequate performance to be achieved and the heading must remain within $\pm 10/15^{o}$ for desired/adequate performance, only when passing through the gates and during the stabilisation phase. Speed and height constraints are also defined and apply throughout the duration of the task, speed ±5/10knots desired/adequate and ±10/15ft desired/ adequate respectively.

To determine the Level 2/3 HQs boundary for the tilt-rotor aircraft, the task must be flown in all three, flight modes as each mode is piloted with a different combination of controls as demonstrated by Table 2:

Table 2 Tilt-Rotor Roll Control

Mode	Helicopter	Conversion	Aeroplane
Roll Control	Differential Collective	Differential Collective & Ailerons	Ailerons

Helicopter Mode

The roll-step task was flown only by pilot A in helicopter mode at (60 knots) as it was felt that roll control in the faster conversion mode would drive the maximum tolerable differential collective rate limit, as the control strategy adopted is similar for these two flight modes. The results recorded for the baseline configuration and for rate limits of 3^{o}/sec and 1^{o}/sec are presented in Figure 6. Subplot 1 demonstrates the flight path for each case. All three cases met adequate performance criteria throughout the task, however as rate limiting was increased to 1^{o}/sec, pilot A struggled to maintain adequate height during the stabilisation phase. An HQR 5 was returned for both the baseline and 3^{o}/sec configurations and an HQR 10 for the 1^{o}/sec case. The pilot commented that although adequate performance was marginally achieved, control was lost shortly after the task was finished due to a roll/yaw PIO.

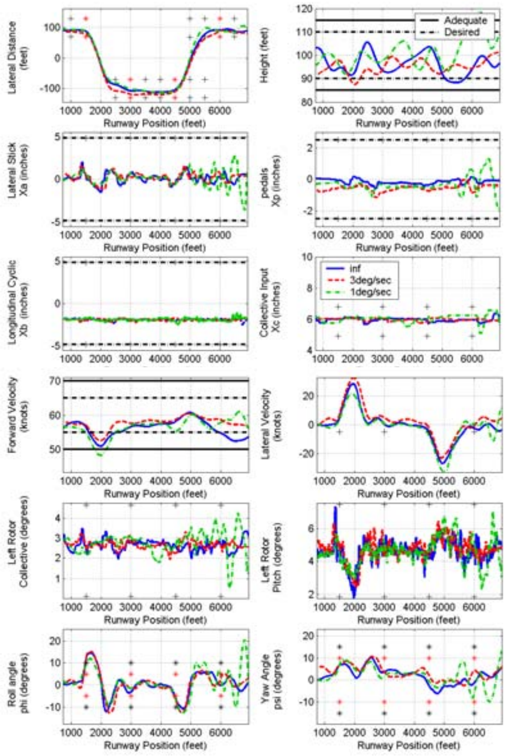


Figure 6 Roll-Step With Infinite, 3^{o}/sec and 1^{o}/sec Rate Limits

Conversion Mode

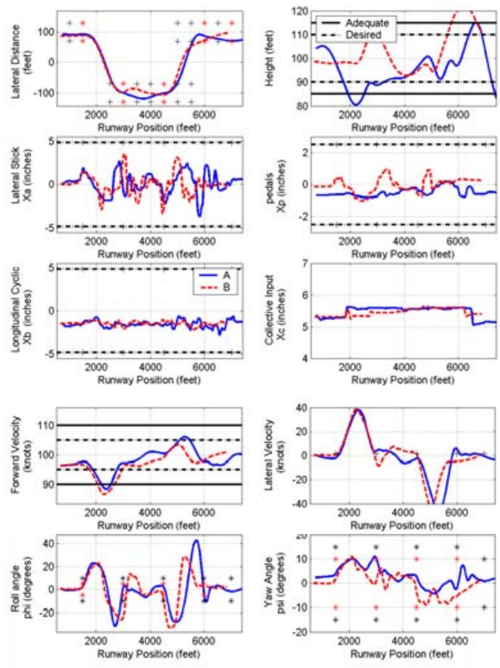


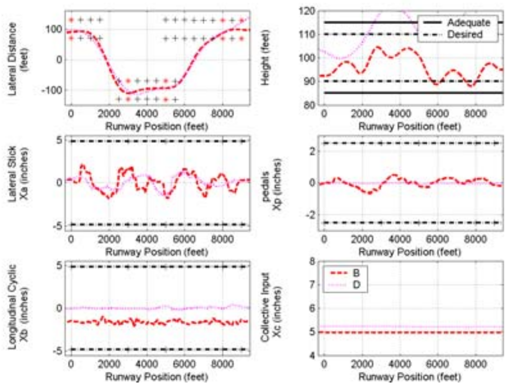
Figure 7 Roll-Step 4^{o}/sec Rate Limit

The roll-step was flown in conversion mode at 100 knots with 60^{o} nacelle tilt. Pilots A and B awarded HQRs 5 and 4 respectively for the baseline aircraft. A rate limit of 4^{o}/sec was then applied and the pilots asked to fly the degraded configuration, the recorded states and controls can be viewed in Figure 7. Both pilots struggled to maintain altitude and speed, to realign on the left runway edge and to complete the stabilisation phase. For example, pilot A exceeded bank angles of 40^{o} in order to reduce lateral velocity and realign on the runway edge. Although this was an extreme manoeuvre, he returned an HQR 5, while pilot B returned an HQR 7. Examination of Figure 7 reveals that both pilot A and C were actually just outwith adequate performance in height and speed suggesting that the Level 2/3 boundary was reached. Therefore, the recommended maximum tolerable rate limit for this task is 4 ^{o}/sec.

Aeroplane Mode

The helicopter and conversion modes were flown with an aspect ratio of 0.133 (1500ft along the runway with a 200ft turn to the right/left). However, as the aeroplane mode speed is necessarily higher, the aspect ratio is halved to 0.066 (3000ft along the runway with a turn to the right/left across 200ft).

Pilots A and D returned HQR 5 for the baseline case, employing similar control strategies, they met desired performance criteria for roll and yaw and adequate performance in height and speed. Pilot B however struggled to maintain adequate height and speed and returned an HQR 6. The rate limit was then increased to 3^{o}/sec and a selection of the recorded states and controls are presented in Figure 8. Pilot B returned an HQR 5 and as a result rate limiting was increased to 2^{o}/sec, also shown in Figure 8 for Pilot D as the Level 2/3 boundary was not identified, where an HQR 5 was still returned. These plots do however suggest that the pilots struggled to return to a trimmed flight condition during the stabilisation phase and that adequate height performance was not achieved.



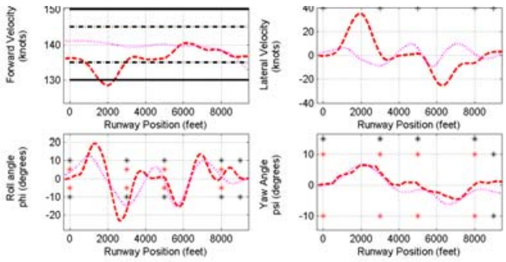


Figure 8 7^{o}/sec and 2^{o}/sec Rate Limit

Roll Axis Maximum Tolerable Rate Limiting Recommendation

Roll in helicopter mode is governed through differential collective, where the maximum tolerable rate limit was found to be 3^{o}/sec (50%/sec), while ailerons govern roll in aeroplane mode, and 4^{o}/sec is recommended as the maximum aileron rate limit as this was the lowest rate limit where the task and stabilisation phase were adequately completed (even though Level 2 HQRs were returned for lower rate limits). Roll in conversion mode, which is controlled through a combination of differential collective and aileron was found to be the worst case with a recommended maximum tolerable rate limit of 4^{o}/sec. Thus the maximum tolerable recommended rate limit is based upon the worst case, which is 4^{o}/sec.

Hover-Turn

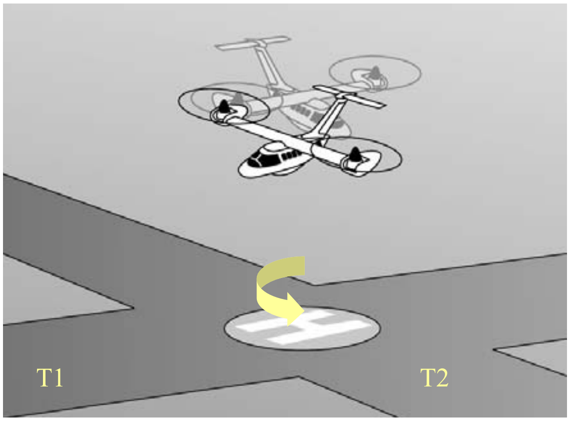


Figure 9 Hover-Turn task

The hover-turn was flown at a helipad, which was positioned at the intersection of two perpendicular taxiways, illustrated as T1 and T2 in Figure 9. The task was to begin from hover aligned with the centreline of Taxiway 1, then turn 90^{o} to the left, using the centreline of Taxiway 2 as a finishing reference point. The severity or 'level of aggression ' of the task was varied during the trials such that the pilot was required to complete the task in less time, by applying larger control inputs which, in theory will drive the HQRs towards or into Level 3 and also expose any potential for PIOs or cliff edges in the aircraft response (the low aggression turn was 20 seconds long, the moderate aggression task 15 seconds). In order to meet the performance requirements for the hover-turn task, the pilot must begin the task at 25ft above the helipad. Height must be maintained throughout the task within ±5/10ft to achieve desired/adequate performance. Finally, a 5 second stabilisation period is included.

Low Aggression

Pilots A and B returned HQR 4s for the no rate limit case. The next configuration flown was with a rate limit of 2.8°/sec, which can be viewed in Figure 10. Although the first 15 seconds of the task flown by Pilot A are not illustrated, they are not the critical phase of the task. A PIO occurred in the stabilisation phase when full right pedal was applied in order to reduce the yaw rate and bring the tilt-rotor to a hover aligned with the centreline of Taxiway 2. The pilot however was able to stabilise the PIO by taking feet of the pedals, quickly damping out the yaw oscillation. Pilot B also flew the task, returning an HQR 4, where pedals were slowly displaced then untouched for the duration of the turn and finally slowly centralised to arrest the yaw rate.

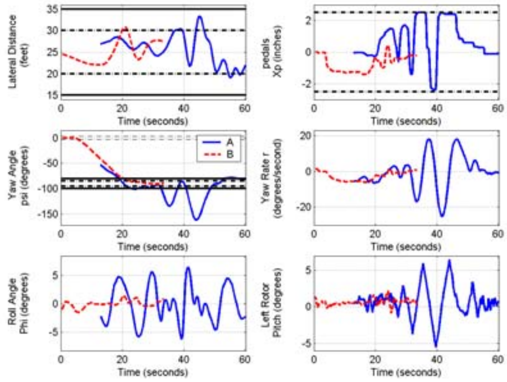


Figure 10 Low Aggression Hover-Turns 2.8°/sec Rate Limit

Moderate Aggression

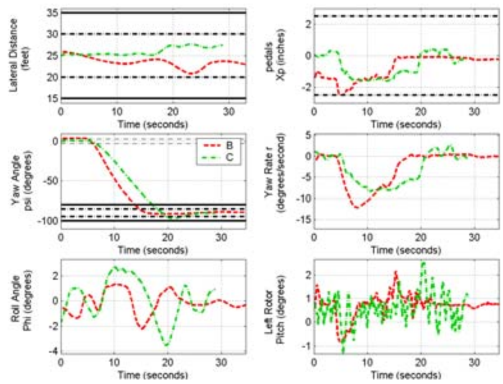


Figure 11 Moderate Aggression Hover-Turns 2.8°/sec (35%/sec) Rate Limit

When aggression level was increased (by reducing task time), pilots B and C returned HQR 4s for the baseline configuration (no rate limiting). Rate limiting was again increased to 2.8°/sec and a selection of the recorded time histories plotted in Figure 11. Both pilots returned an HQR 6 and added that although a PIO was not encountered, they had to operate with a very low gain and if control inputs became slightly out of phase, an uncontrollable PIO may have been encountered.

Yaw Axis Maximum Tolerable Rate Limit Recommendation

The moderate aggression task results suggest that a rate limit of 2.8°/sec predicts the level 2/3 HQs boundary, however Pilot A experienced a severe PIO for this case in the low aggression task, thus in order to adequately achieve Level 2 HQs, a rate limit of 4°/sec is recommended.

Acceleration-Deceleration

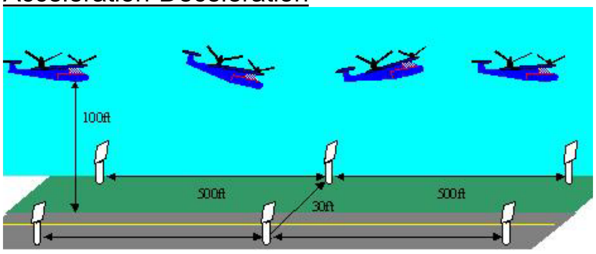


Figure 12 Acceleration-Deceleration Task

The acceleration-deceleration task assesses both the heave and pitch axes in helicopter mode and identifies undesirable couplings between the longitudinal and lateral axes. The task was to start from hover at a set of gates aligned with the side of the runway as demonstrated in Figure 12, then accelerate forward with a designated nose down pitch attitude, maintaining a height of 100ft until the following set of gates is reached (gates are 500ft apart). The pilot is then required to decelerate whilst maintaining constant altitude, reaching a hover at the next set of gates and stabilise for 5 seconds.

The task aggressiveness was limited by the flight simulator field of view, which has a range of approximately ±20°, thus the pilots were asked to accelerate with 15° pitch nose down. It is evident from Figure 13 that when a rate limit of 3°/sec was applied, pilots B and C adopted different strategies, beginning and ending the task at different points. This was because the pilots had to line up behind the gates in order for them to be visible in the chin window, thus the start and finish position was more difficult for the pilot to determine than was originally anticipated. Figure 13 subplot 1 shows that the first pilot began the task almost exactly level with the reference gates and finished 180ft behind them while a second pilot initiated the task 200ft behind the start point, again to use the gates as a visual cue but finished level with the end gates. Pilot B returned an HQR 5. He commented that although pitch was more sluggish, it was more predictable than for the baseline case but still required considerable pilot compensation. Pilot C also returned an HQR 5 but felt a controllable roll PIO was induced. Rate limiting was further increased (rate limit reduced) to 2^{o}/sec in order to establish the level 2/3 handling qualities boundary.

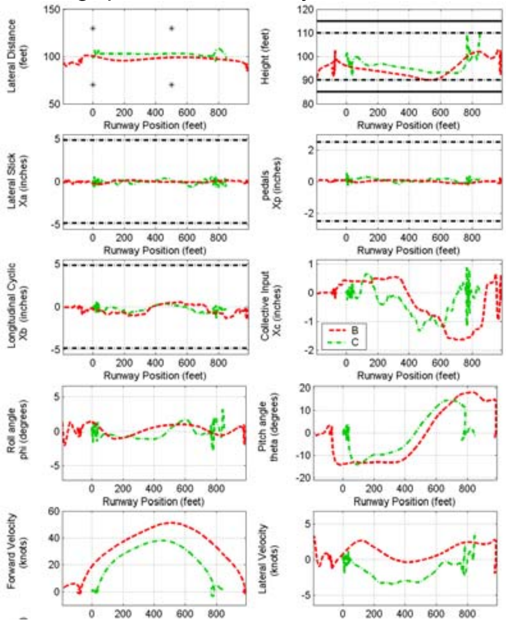


Figure 13 Accel-Decel Task With 3^{o}/sec Rate Limit

Pilot C attained desired performance criteria throughout most of the task; however, when approaching the hover and stabilisation phase, all control was lost and an HQR 10 was returned. Pilot B managed to complete the task satisfactorily, returning an HQR 6, but commented that he was acting with a very low gain.

Pitch Axis Minimum Tolerable Actuation Rate Recommendation

Although the task was flown over two trials and only with two pilots, there is a good correlation between their results for the acceleration-deceleration task. The minimum tolerable rate limit is therefore proposed as 3^{o}/sec. Even though Pilot B returned an HQR 6 for a worse case, this is not recommended due to the extensive workload and possibility of encountering a PIO.

Bob-Up

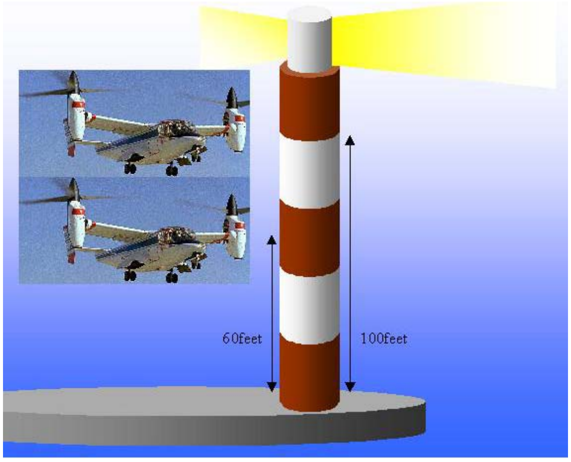


Figure 14 Bob-Up Task

In order to assess the tilt-rotor heave axis controllability and handling qualities, two tasks were defined, the heave-hop which addresses the vertical axis in conversion and aeroplane modes (ref 6), and the bob-up, which examines the helicopter mode as considered in this section. The bob-up task was selected for this series of HQs trials because it assesses the ability of the tilt-rotor to initiate/stop a vertical rate (ref 2) and also will identify any undesirable cross coupling between collective and pitch, roll or yaw motions. These are both important considerations when examining actuator rate limiting as too much rate limiting could excite a PIO in any of the three axes and degrade height control.

If the bob-up task is to be performed successfully in the simulator, good height cueing is required, thus the task was flown using a lighthouse as a height reference as shown in Figure 14. The task began from a stabilised hover aligned with the centre point of a dark concentric hoop at 60ft, then the pilot was asked to climb to an altitude of 100ft, using the join between the top of the next white hoop and the bottom of the next dark hoop as a reference finishing position. Finally a 5 second stabilisation period was again required.

Pilots B and C employed the same strategy for the no rate limit case and the tasks were completed within desired performance levels, with HQR 5 and 4 being returned respectively. Figure 15 demonstrates the time histories recorded when rate limiting was applied at 3^{o}/sec. Pilot C still met the desired performance criteria and reflected this by returning an HQR 3, commenting that the workload was low to moderate. Pilot B however, graded the task as HQR 6.

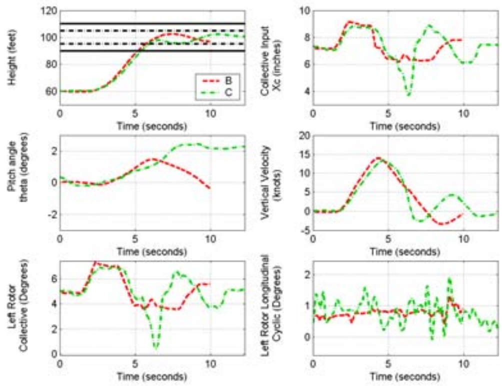


Figure 15 Bob-Ups 3°/sec Rate Limit

Helicopter Mode Heave Axis Maximum Tolerable Rate Limit Recommendation

Although neither pilot actually recorded an HQR 7 or worse in this set of experiments, the recommended maximum tolerable rate limit for this axis is 4°/sec. This is simply due to the possibility of encountering a cliff edge and inducing a PIO with a lower rate limit.

Heave-Hop

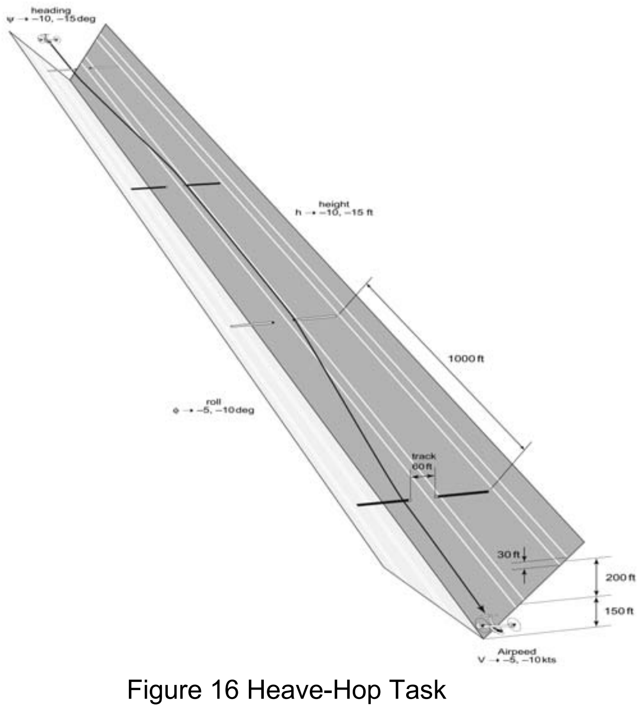


Figure 16 Heave-Hop Task

The heave-hop (ref 8) task examines both the pitch and heave axis of the tilt-rotor in aeroplane mode (although it can also be used to assess HQs in helicopter and conversion mode (ref 9)). The task begins with the pilot entering a valley at a reference speed and height of 150ft. The heave-hop task consists of various pilot cues illustrated in Figure 16, the first of which is a white line at ground level that marks out the run-up to the valley where the heave-hop task is located. When entering the valley, two sets of white tramlines are visible, the first is located at 140ft and 160ft respectively to mark the desired performance boundaries for starting the task and the second set is located at 340ft and 360ft to mark the desired performance boundaries at the end of the task.

A series of alternating black and white posts are located at 1000ft intervals along the valley at a height of 250ft. The task is then, starting at the designated post, climb to the desired altitude by the time the next post of that colour is reached, then stabilise within the marked tramlines until the end of the valley. The pilot is required to maintain speed within ±5/10knots desired/adequate, while both pitch and yaw are ±5/10° for desired/adequate performance respectively to be achieved.

Figure 17 charts the time histories for pilots B and D flying the heave-hop task with a 3°/sec rate limit. As both pilots apply longitudinal stick the aircraft pitches upwards, causing an increase in height and a decrease in speed. Both pilots then applied collective to maintain speed. Pilot B returned an HQR 4, however pilot D failed to maintain adequate speed or height during the stabilisation phase, encountering a roll oscillation that drove an HQR 7 rating.

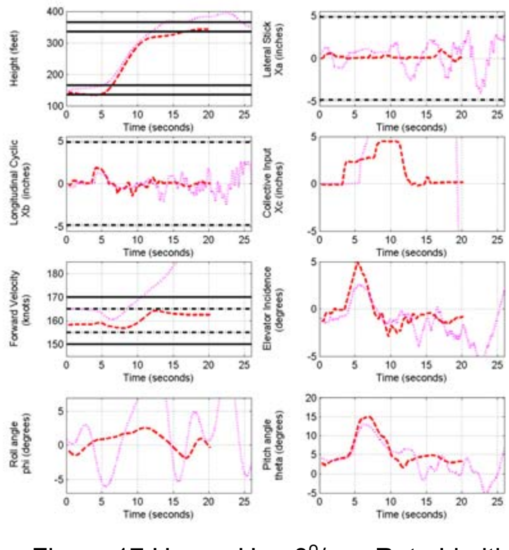


Figure 17 Heave-Hop 3°/sec Rate Limiting

Although pilot D returned an HQR 7 for the 3°/sec case, he flew the aircraft with a rate limit of 4°/sec returning an HQR 5. This suggests that this actuation rate limit configuration is preferable to the baseline case or that with practice he became more familiar with the aircraft and task, such that his HQRs improved accordingly.

Aeroplane Mode Heave Axis Maximum Tolerable Rate Limit Recommendation

The recommended maximum tolerable rate limit for the aeroplane mode pitch axis is therefore selected as 4^{o}/sec because pilot D found this to be Level 2 and although pilot B did not fly this configuration, he returned a level 2 rating for a more severe degradation.

Degraded Failure Conclusions

Results have been presented from the simulation trials at UoL, which aimed to identify the lowest tolerable rate limit for each axis that described Level 2 Handling Qualities. Table 3 presents a summary of these results.

It is evident from Table 3 that the maximum tolerable rate limit for the collective axis is 4^{o}/sec, whereas it is 3^{o}/sec for the differential collective axis. As a result, the maximum tolerable rate limit for the collective/differential collective actuator must be 4^{o}/sec. This is also true for the longitudinal/differential longitudinal cyclic actuator, where the maximum tolerable rate limits are 3 and 4^{o}/sec respectively. Again the higher value must be selected as the maximum tolerable rate limit. In aeroplane mode, there is no cross coupling between the control axes, thus the recommended rate limit for aeroplane mode is also 4^{o}/sec.

Table 3 Minimum Actuator Rate Limits

Control		Rate Limit	
		(°/sec)	(%/sec)
Differential Collective	Helicopter Mode	3 °/sec	50%/sec
	Conversion Mode	4 °/sec	66%/sec
Collective		4 °/sec	30%/sec
Longitudinal Cyclic		3 °/sec	15%/sec
Differential Longitudinal Cyclic		4 °/sec	50%/sec
Ailerons		4 °/sec	20%/sec
Elevator		4 °/sec	20%/sec
Rudder		---	---

The helicopter, conversion and aeroplane mode maximum tolerable rate limit recommendations are 4^{o}/sec, thus the final, overall maximum tolerable rate limit recommendation for the Flightlab XV-15 aircraft is 4^{o}/sec.

Malfunction Failures

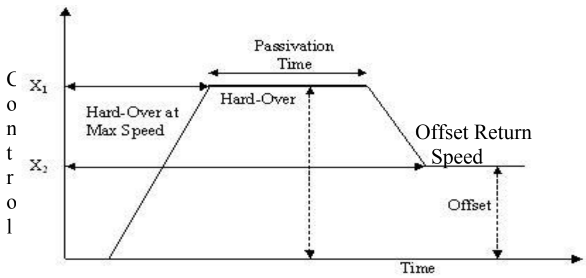


Figure 18 Transient After Failure

In the event of a malfunction failure, it is necessary to know the maximum tolerable transient of the failed control surface. The failure consists of the five parameters illustrated in Figure 18. The first critical parameter in the 'transient after failure' is the maximum actuation speed that forces the control surface to the hard-over position which is 1.25 times larger than the operational actuation rate (actuator plus 25% loads). The maximum tolerable hard-over position is the maximum control surface deflection and is determined in conjunction with the passivation time (the time that the control surface spends at the hard over position). Finally the offset value and offset return speed are the position the control surface is returned to after the malfunction has been identified and the actuation speed which the control surface is returned at (2/3 operational actuation speed).

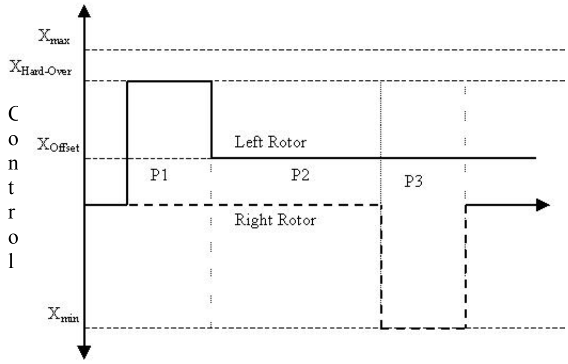


Figure 19 Desired Failure Transient Control Input Profile

The level of failure transient severity was defined by Eurocopter from the international standards (ref 2) and (ref 10). Using these requirements, it is possible to undertake a failure transient analysis, where the failure transient is simulated by moving the control surface X in question as illustrated in Figure 19. The first phase of the input P1, is to apply a step input $X_{Hard-Over}$ to the malfunctioning control surface at hard-over speed that results in the required control surface hard-over position. Phase 2 (P2) then decreases the $X_{hard-Over}$ position to X_{offset} at the offset return speed after a passivation time. Finally phase 3 (P3) represents the end of the hands-off phase where the pilot applies a full control input to arrest the attitude change (clearly this is only possible if two control surfaces exist in the control function such as aileron whereby if the left aileron fails, the pilot can still control the right aileron. If the rudder malfunctions, it is returned to an offset position and the aircraft flown side slip). Thus P1 and P2 must equal the hands-off time.

This control surface input profile was applied to the Flightlab Erica model and varied to give a range of hard-over values and the corresponding passivation times. Figure 20 demonstrates the resultant aileron time histories and corresponding roll angle for the Level 2 case with 3^{o} offset.

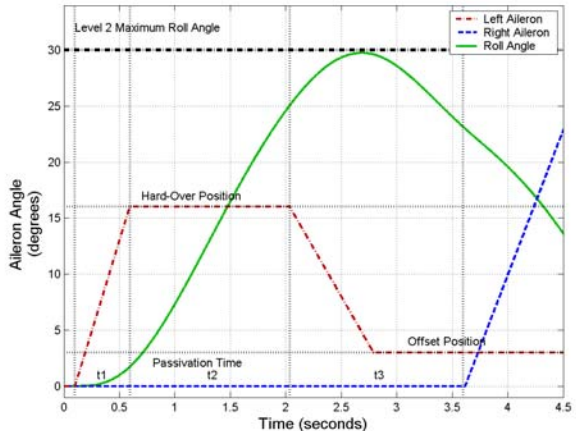


Figure 20 Failure Transient Example from the Flightlab XV-15

Figure 21 demonstrates the effect of aileron hard-over position as passivation time increases for the Level 1, 2 and 3 requirements when the offset is 0^{o}, (the failed aileron is returned to trim). Clearly the maximum hard-over position for each handling qualities level requires the smallest passivation time if the attitude limits are not to be exceeded. Thus, as the aileron hard-over position is decreased, the associated passivation time increases for the same HQs.

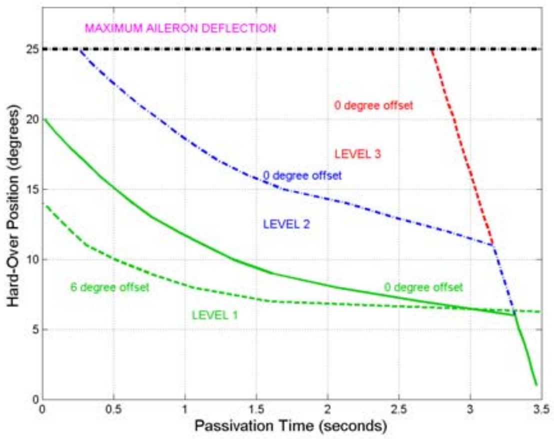


Figure 21 Failure Transient for Flightlab XV-15

If Level 1 HQs are to be achieved a full aileron deflection is not tolerable. In this case a 20^{o} hard-over is tolerable if the malfunctioning left aileron is returned to trim immediately. For Level 2 to be achieved, a full deflection is tolerable but must be pacified within 0.3 seconds. Finally a full aileron hard-over failure does not exceed the level 3 criteria within the specified hands-off time. Figure 21 also demonstrates the effect on the Level 1 failure transient if the offset is not the trim value. As the magnitude of the offset from trim increases, the maximum hard-over position decreases, for example, if Level 1 HQs are to be maintained, a 6^{o} offset reduces the maximum hard-over position to 14^{o}. lists the worst tolerable malfunction failure for each of the control function in aeroplane mode.

Table 4 Worst Case Malfunction Failures in Aeroplane Mode

Control Function	Level	Hard-Over (deg)	Offset (deg)	PassivTime (secs)
Aileron	1	14	6	0
	2	25	11	0.17
	3	25	25	3.25
Elevator	1	3	1	0
	2	4	2	0
	3	5	4	0
Flap	1	12	8	0
	2	16	15	0
	3	18	18	0
Rudder	1	7	1	0
	2	7	2	0
	3	11	4	0
Wing	1	7	2	0
	2	9	3	0
	3	14	12	0

Loss of Function and Back Up Modes

Although the reported simulation trials focused on degraded analysis using the Flightlab XV-15 tilt-rotor model at UoL, the XV-15 does not contain one of the key features of the AGUSTA-WESTLAND ERICA configuration, a tilting wing which reduces the power required in hover. As a result, the tilt-wing failure was performed in a later simulation trial when the ERICA configuration was 'released' to UoL.

The tilt-wing failure analysis was broken into two assessments. The first test was to determine the affect of one tilt-wing failure in aeroplane mode and to identify the maximum tolerable failure position associated with one tilt-wing loss (performed only with right tilt-wing failure as the aircraft is symmetrical). The second test was to determine if it was possible to convert back to helicopter mode and hover with one tilt-wing failed in the position identified in the first test (conversion from helicopter mode was also tested however it was concluded that if a tilt-wing failure occurs in helicopter mode, conversion will not be permissible thus further analysis was not required). These two tests are now discussed in further detail.

One Wing Failure In Aeroplane Mode

ERICA was trimmed at 160 knots with SCAS on, height and position were not specified. When the pilot was satisfied with the trim condition, a series of tilt-wing failures were implemented. Only the worst case is shown here which was a 10^o right wing deflection and the pilot was required to wait 1.5 seconds before taking corrective action. The resultant time histories can be viewed in Figure 22. The affect of the right tilt-wing failure forced the pilot to apply increasing amounts of right lateral stick, until almost full stick deflection was required to overcome the induced roll rate.

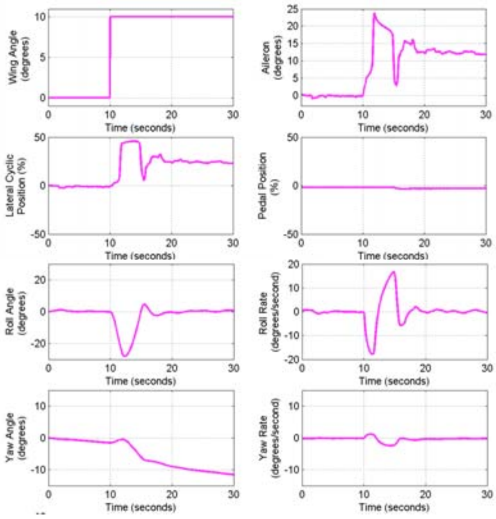


Figure 22 Right Wing Failure and Capture at 10^o with 1.5sec Corrective Action Time Delay

Although it may be possible to withstand larger one tilt-wing failures, the failure would be detected and frozen before 10^o deflection is reached, therefore there was no need to assess more severe one tilt-wing failure conditions in aeroplane mode.

<u>Conversion From Aeroplane Mode To Hover With One Wing Failure</u>

During the conversion process to helicopter mode, a 10^o one tilt-wing failure had little affect on the task and the lateral stick becomes almost centred. Finally, during the hover capture phase the functional tilt-wing moves from 0^o to 80^o as speed is reduced from 80 knots while the failed tilt-wing remains at 10^o deflection. As a result, the left tilt-wing produces a drag force that yaws the aircraft to the left during the deceleration phase, where the pilot requires only small amounts of lateral stick and pedal to correct.

<u>Use of Helicopter Mode Controls as a Back Up in the Event of an Aeroplane mode Function Failure</u>

The tilt-rotor aircraft has the unique possibility of utilising the helicopter mode controls if there is a control failure in aeroplane mode. Three possible back-up solutions are envisaged in Table 5 provided the failed aeroplane mode control surface is returned to a position which does not adversely affect the handling qualities.

Table 5 Aeroplane Mode Backup Controls

Failed Control Surface	Backup Control
Ailerons	Differential Longitudinal Cyclic
Elevator	Longitudinal Cyclic
Rudder	Differential Collective

These backup control modes were assessed using the Flightlab XV-15 model. The backup modes were implemented in the Flightlab XV-15 control system via a series of switches, where upon switching off the aeroplane mode control, the backup control automatically came online. A malfunction was also built into the aeroplane mode control whereby the simulator driver had the ability to adjust the control surface deflection when the failure was implemented.

The key question in this analysis was 'what is the maximum tolerable hard over control surface failure deflection/offset which still allows the pilot sufficient control authority with the back up configuration?'. The following section addresses this question by considering the results from simulation trials for the three possible backup solutions to a loss or malfunction of an aeroplane mode control.

<u>Use of Differential Collective as a Backup Control for loss of Rudder</u>

The dutch-roll mode is mainly controllable by the rudder, thus with no rudder, there is no possibility of stabilizing the aircraft at high altitude unless a back-up solution exists. Use of differential collective was therefore proposed as a back up solution to rudder loss and simulated at high altitude. The pilot was asked to fly in trim at 200 knots indicated airspeed at a height of 25000ft. The rudder was then failed and control passed to differential collective, still via pedals.

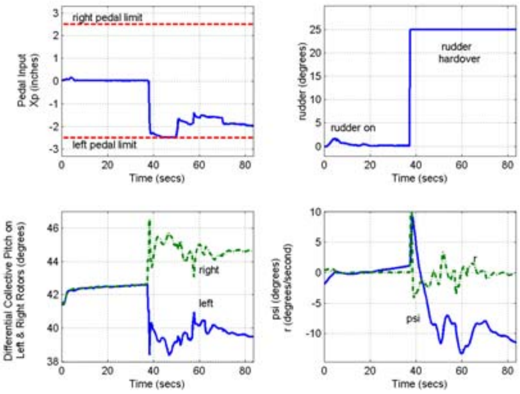


Figure 23 Rudder failed at 25^o and control passed to Differential Collective

The first of the four subplots in Figure 23 illustrates the control activity on the pedals after rudder failure occurred. When the failure was implemented, the rudder was forced instantaneously to its hard over position (maximum possible deflection) which caused the aircraft to yaw to the right. Then, almost immediately the pilot applied full pedal in order to counteract the yawing moment with differential collective.

From the yaw and yaw rate plot, it is evident that although the dutch-roll mode is not an issue for the Flightlab XV-15 model at high altitude, there is not enough control authority to maintain heading when a rudder hard over deflection of 25^o occurs as the heading continues to deviate from the desired flight path with time. It should however be noted that the gearing ratio between pedal input and differential collective in this case was 1^o/inch whereas in helicopter mode a gearing ratio of 1.6^o/inch is used. This suggests that a higher gearing ratio can be used giving the pilot more control power in the backup case than was tested here.

<u>Use of Differential Longitudinal Cyclic as a Backup Control for loss of Ailerons</u>

Use of differential longitudinal cyclic as a backup control to aileron loss was again assessed at 25000ft and at 200 knots indicated airspeed. The ailerons were both failed initially at 0^o (trim) such that the failure did not disturb the flight condition.

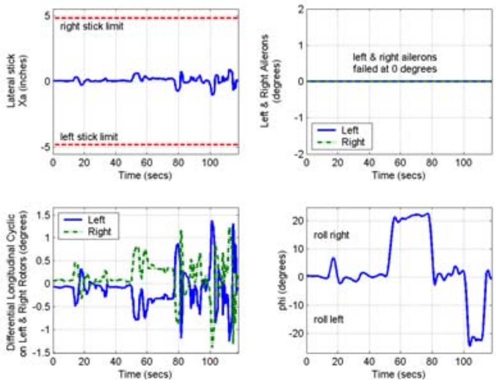


Figure 24 Aileron failed at 0^o (trim) and control passed to Differential Longitudinal Cyclic

It is evident from Figure 24 that as the ailerons are at 0^o when failed, the pilot is not immediately aware of the failure as the aircraft remains in steady level flight, thus the plots do not clearly illustrate the failure point. However, it is evident from the differential longitudinal cyclic plot that failure has occurred as this control and not the ailerons, is commanding roll. To test the backup mode control power, a 50 knot gust was applied and the pilot asked to attempt to maintain a trimmed flight. Although the gust strength time history is not plotted here, it is evident that it is first applied at approximately fifty seconds, causing the aircraft to roll almost 25^o, whereby the pilot maintains this bank angle until the gust is removed 30 seconds later. The corresponding stick activity and differential longitudinal cyclic applied by the pilot are displayed in the first and third subplots respectively. Clearly differential longitudinal cyclic is a suitable backup control if the ailerons fail or can be returned to 0^o after a failure, but the maximum tolerable failure positions must also be identified.

Figure 25 shows the state and control time histories recorded when the left aileron was failed at –12^o and the right aileron failed at 12^o. It is evident from the lateral stick plot that approximately 2 inches of lateral stick is required to counteract the rolling moment produced from the aileron offset. Figure 25 also demonstrates that when a gust is applied (a 50 knot gust at approximately 35 seconds in this case), sufficient roll control authority remains to adequately stabilise the rolling moment.

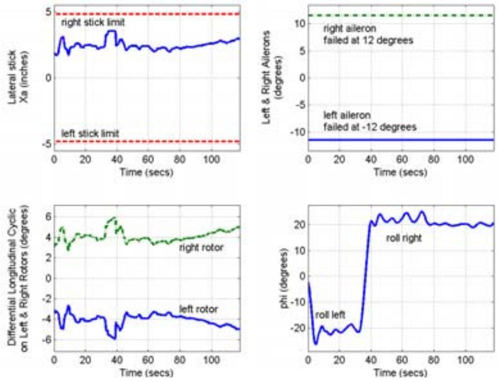


Figure 25 Left & Right Ailerons failed at -12^o & 12^o respectively and control passed to Differential Longitudinal Cyclic.

<u>Use of Longitudinal Cyclic as a Backup Control for loss of Elevator</u>

The final backup solution is the use of longitudinal cyclic in the event of elevator loss. Figure 26 demonstrates this, where the elevator can be seen to fail after approximately 45 seconds and control is passed to longitudinal cyclic for the same test conditions described previously (200 knots at 25000ft).

When the elevator was failed in its trim condition and control passed to longitudinal cyclic, longitudinal cyclic blade pitch was immediately applied which caused a pitch down moment which the pilot has to correct by applying 2 inches of aft longitudinal stick. It is evident from this plot that even if the elevator is failed in the trim position, the pilot must use approximately

50% of the available control power to stabilise the aircraft, thus it must be determined what the maximum tolerable hard-over position is which still allows the pilot to maintain adequate control.

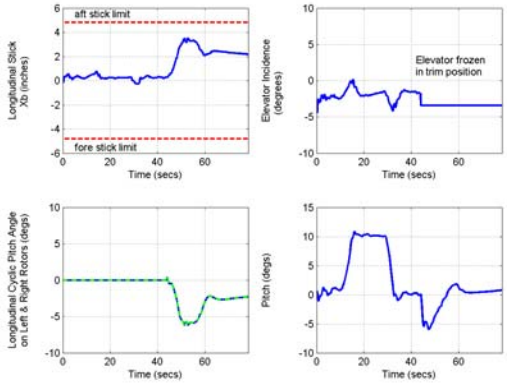


Figure 26 Elevator failed at -3.5° (trim) and control passed to Longitudinal Cyclic

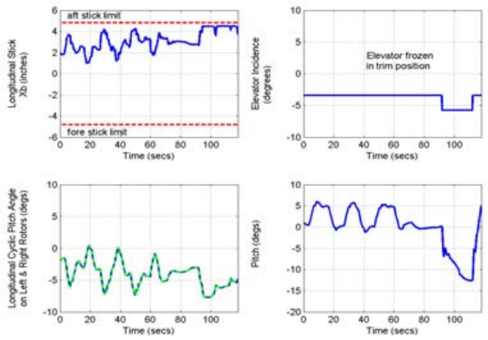


Figure 27 Elevator failed at -6° and control passed to Longitudinal Cyclic

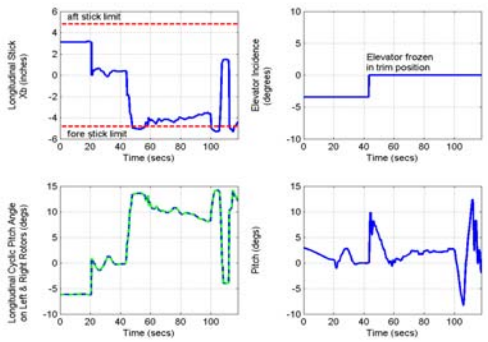


Figure 28 Elevator failed at 0° and control passed to Longitudinal Cyclic

Figure 27 demonstrates the affect the control authority and vehicle response when the elevator was failed at 6°, only 2.5° greater than the trim deflection. The first subplot clearly shows that the pilot has applied full stick after the failure and struggles to maintain control of the aircraft. Figure 28 demonstrates a similar case, this time when the elevator is failed at 0°, and again the pilot is forced to apply full control, however in this case full forward stick.

Back-up Control Recommendation

The loss of elevator appears to be the most critical case, where if it fails out with ±2.5° of the trim state, the pilot is unable to adequately control the aircraft with the backup solution. In the case of failed aileron(s), the pilot has adequate control authority if the failure occurs within ±12° of trim. The use of differential collective as a back up to loss of rudder control proved not to be an issue with the Flightlab XV-15 aircraft.

Concluding Remarks

This paper has reported progress on the development of criteria for handling qualities following control systems failures on a future civil tilt rotor aircraft. Results have been presented from the series of piloted simulation trials held at The University of Liverpool, assessing loss, degradation and malfunction control system failures.

With regard to failures in the actuation system leading to a reduction in actuation rate, the studies have examined the minimum tolerable actuation rate for the FLIGHTLAB XV-15 simulation model, for each axis and flight mode, by flying a range of mission tasks such as the roll-step, heave-hop, bob-up, hover-turn and acceleration-deceleration. The minimum actuation rate that preserved Level 2 HQs was determined for each task/flight mode and found to be 4°/sec.

Although ERICA was not used in the degraded failure assessment, it was shown that a single tilt wing tilt actuation failure of 10° magnitude was ‘acceptable’ and that the pilot could recover and convert back to helicopter mode within Level 2 constraints. Failures were further assessed off-line, within a technique which predicts the maximum tolerable failure transient.

Finally the possibility of using helicopter mode controls as a backup to a loss of an aeroplane mode control function demonstrated that differential collective was a suitable backup control to a full rudder loss if the helicopter mode gearing ratio is applied differential longitudinal cyclic was acceptable in the event of an aileron failure within 12° of neutral and that longitudinal cyclic was only acceptable backup control if the elevator failed within 2.5° of neutral setting.

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