Rotorblade Trailing Edge Flap Failure Modes and Effects Analysis

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As part of the Rotor Embedded Active Control Technology project, this paper reports on the impact of trailing edge flap failures on aircraft Handling Qualities. The primary means of assessing the effects of failure transients in this study is through the ADS-33E-PRF failure transient criteria, where flight path deviations resulting from flight control system failures are classified in terms of Handling Qualities Levels. The rotor blades of the FLIGHTLAB REACT Generic Rotorcraft model used in this study feature NACA0012 aerofoil sections with two flaps, each with an operational range of $\pm 3^{o}$. Two mean settings were considered - the first at 0^{o} and the second at 4^{o} to simulate a cambered aerofoil. This short study focused on two modes of failures: hardover and oscillatory malfunctions, where the flaps oscillate once per revolution. The worst failure case was found to be in the hover-and-low-speed regime for advance ratio 0.1 with a mean setting of 0^{o}, when all flaps suffer phased 1/rev failures, where the resulting rotor hub loads and aircraft response are similar to the effect of a one degree lateral cyclic pitch input. This failure case takes the transient response into the Level 3 Handling Qualities region. In forward flight, all failure transients were found to remain within the Level 1 region. In addition to determining the 'divided attention' failure transients three seconds after a failure occurs, a test pilot performed 'fully attended' Mission Task Elements to assess the effect of the failure on closed-loop HQs, flying the University of Liverpool's HELIFLIGHT-R simulation facility. Results showed that the worst case failures had little effect on the 'fully attended' handling qualities.

1 Introduction

The Rotor Embedded Active Control Technology (REACT) project addresses the use of Trailing Edge Flaps (TEFs)[1,2] which are integrated with the main lifting section of the blade and are deflected harmonically in order to change the lift characteristics of the blade aerodynamic section[3-5]. One aspect of the project, presented in this paper relates to the performance and handling of out-of-balance rotors through a TEF failure modes and effects analysis, establishing severity levels and reliability requirements.

It is vital to ensure that the pilot is able to maintain adequate control of the vehicle following any failure, and any failure transients must also be manageable by the system or pilot. This is achieved by way of a Failure Hazard Analysis (FHA), which begins by determining the type of failure - three possibilities have been envisaged:

- **Malfunction** – The control surface does not move consistently with the input (e.g. hard-over, slow-over or oscillations).
- **Loss of function** – the control surface does not respond to the corresponding control input and is frozen at some value.
- **Degradation of function** – The control surface is still working but with degraded performance.

The primary means of assessing the effects of failure transients in this exercise is through the ADS-33E-PRF[6] failure transient criteria where the effect of the failure is classified as a failure probability in terms of flying hours. This classification is shown in Table 1 where, for example, if a failure is to be classified as being no worse than major, the probability that the failure will occur must be less than once every one thousand flying hours[7]; whereas if a failure is classified as 'catastrophic', it must be designed such that the probability of occurrence is less than 10^{-7} flying hours. The failure severity can also be defined in accordance with Handling Qualities Levels definitions:

- **LEVEL 1**: Performance well within mission and safety standards, workload low
- **LEVEL 2**: Performance just within mission and safety standards, workload moderate to extensive
- **LEVEL 3**: Performance not Attainable; flight safety at risk, workload maximum tolerable to intense
- **LEVEL 4**: High risk of loss of control

Where, for example, a hazardous failure is defined as being Level 3 HQs. The HQs Levels are defined in terms of spatial displacements or transients following failures as defined in Table 2. Failure transient criteria requirements for 'hover–and-low-speed' and 'forward-flight – near Earth' requirements are derived from ADS-33E-PRF[6], while 'Forward Flight up-and-away' spatial displacements from this reference are based upon aircraft operational flight envelope. However, as the model used in this study does not have a clearly defined operation flight envelope, 'Forward Flight – up-and-away' failure transient criteria are derived based on those presented by Cameron, Padfield[8] and are listed in *Table 2.*

Table 1: Level For Rotorcraft Failure States

PROBABILITY OF ENCOUNTERING	*Failure Effect*	*WITHIN OPERATIONAL FLIGHT ENVELOPE*	*WITHIN SERVICE FLIGHT ENVELOPE*
Level 2 after failure	*Major*	*< $2.5x10^{-3}$ per flight hr*	
Level 3 after failure	*Hazardous*	*< $2.5x10^{-5}$ per flight hr*	*< $2.5x10^{-3}$ per flight hr*
Loss of control	*Catastrophic*	*< $2.5x10^{-7}$ per flight hr*	

Table 2: Failure Transient Criteria

	FLIGHT CONDITION		
	HOVER & LOW SPEED	***FORWARD FLIGHT***	
		NEAR EARTH	***UP-AND-AWAY***
Level 1	3^o pitch and roll attitude change 0.05g n_x, n_y, n_z No recovery action for 3 seconds	HOVER & LOW SPEED requirements apply	20^o roll attitude 10^o pitch attitude 5^o yaw attitude No recovery action for 3 seconds
Level 2	10^o pitch and roll attitude change or 0.2g acceleration No recovery action for 3 seconds	HOVER & LOW SPEED requirements apply	30^o roll attitude 15^o pitch attitude 10^o yaw attitude No recovery action for 3 seconds
Level 3	24^o pitch and roll attitude change or 0.4g acceleration No recovery action for 3seconds	HOVER & LOW SPEED requirements apply	60^o roll attitude 30^o pitch attitude 20^o yaw attitude No recovery action for 3 seconds

This short study focuses on two modes of TEF malfunctions:

- Hardover malfunction – where the TEF moves rapidly to the maximum deflection position (positive or negative)
- Oscillatory malfunction where the TEF oscillates with a frequency of 1/rev.

Results from both failure types are presented for a wide range of TEF failure combinations allowing the most severe failure cases to be identified. Results from piloted simulations are also presented where the identified worst case failures were induced while a test pilot performed predefined Mission Task Element (MTEs) at the University of Liverpool's HELIFLIGHT-R simulation facility[9].

2 REACT Generic Rotorcraft Model

The model created for this study was the RGR (REACT Generic Rotorcraft) model, developed at UoL using FLIGHTLAB. The RGR rotor blades are constructed using NACA0012 aerofoil, modelled as rigid beams which are split into eight user-defined grid elements for aerodynamic load computations. The inboard TEF has airloads calculated at blade aerodynamic sections 3 and 4 while the outboard TEF is located as aerodynamic section 7. Within the FLIGHTLAB aero options, the Quasi-Steady option was selected which models a two dimensional aerodynamic segment with lift, drag and pitching moment defined as non-linear functions of angle of attack and Mach number. The Peters-He three-state induced flow model was selected. The NACA0012 lift coefficients applied to the RGR model are shown in Figure 1.

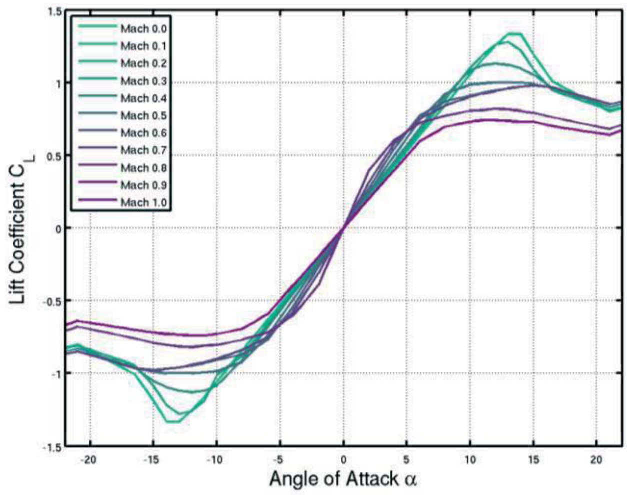

Figure 1: NACA 0012 Lift Coefficients vs. Angle of Attack for a range of Mach Numbers

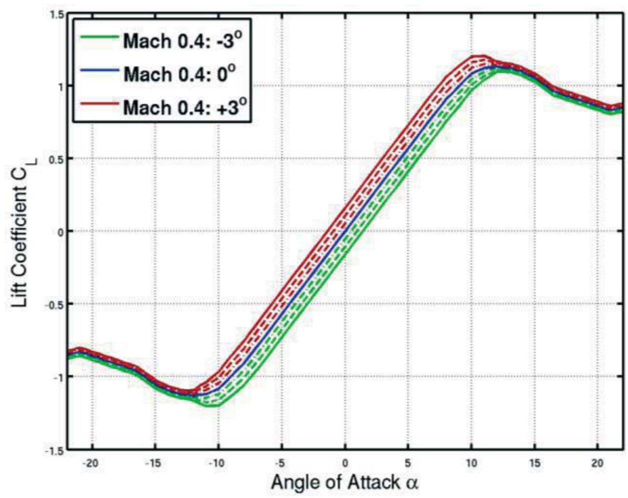

Figure 3: NACA0012 C_L vs. α from $\pm 3^o$ TEF deflection at Mach 0.4

2.1 Modification of Aerofoil Tables for TEF

The table lookup change in lift and drag coefficients (ΔC_L,ΔC_D) from the trailing edge flap deflection were derived by Agusta-Westland using MSES (2D Euler code with strongly coupled boundary layer)[10] for a 1^o deflection. The ΔC_L with α for a range of Mach numbers, for a 1^o deflection is shown in Figure 2. Figure 3 shows the C_L vs. α curves from TEF deflections in 1^o increments at Mach 0.4 for the 0^o TEF setting. This is only a very simple model in order to allow the completion of the airfoil tables for all numerically possible flap deflection angles. Of course, the real aerodynamic behaviour of the trailing edge flap is much more complicated and has to be measured or calculated by CFD[11].

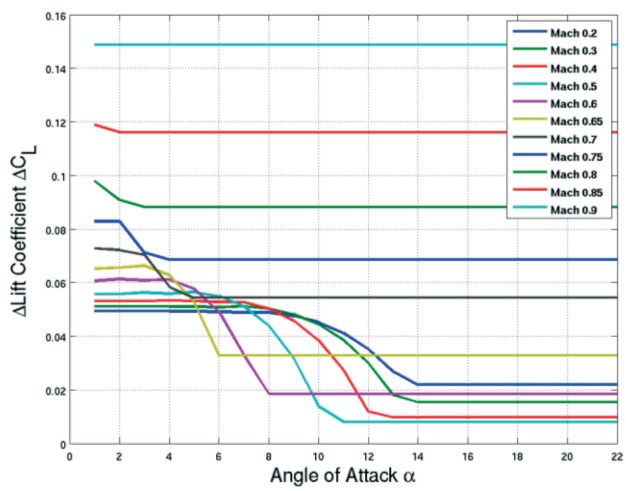

Figure 2: NACA0012 ΔC_L from a 1^o TEF deflection varying with Mach number

2.2 Rotor verification with an Isolated Rotor

The NACA0012 rotor blade with TEFs was applied to an isolated rotor model to verify the correct implementation of the TEFs and NACA0012 data. Figure 4 shows the C_L of each of the eight aerodynamic blade sections on rotor blade 1 with and without hardover malfunctions on the inboard TEF (sections 3 and 4). Figure 5 illustrates C_L on blade 1 when both the inboard and outboard TEFs have a hardover malfunction.

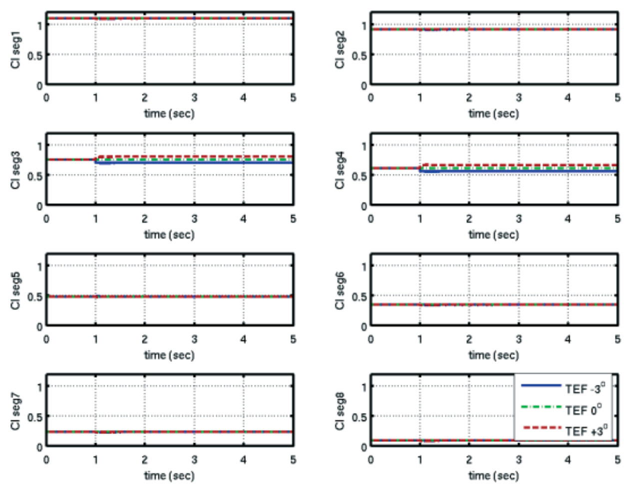

Figure 4: Isolated Rotor model: Blade 1 inboard TEFs hardover

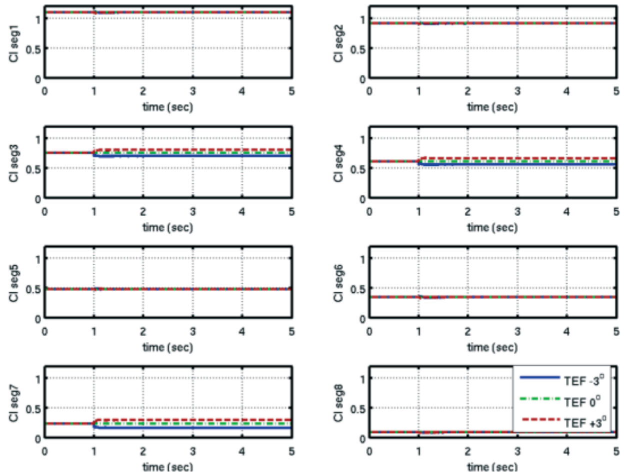

Figure 5: Isolated Rotor model: Blade 1 inboard & outboard TEFs hardover

2.3 FLIGHTLAB RGR simulation model

Figure 6 illustrates the C_L of each of the eight aerodynamic blade sections on rotor blade 1 for no failures and when hardover malfunctions are simulated on the inboard and outboard TEFs (0^o setting). The aircraft response to this failure is shown in Figure 7, where the aircraft yawed almost five degrees in three seconds.

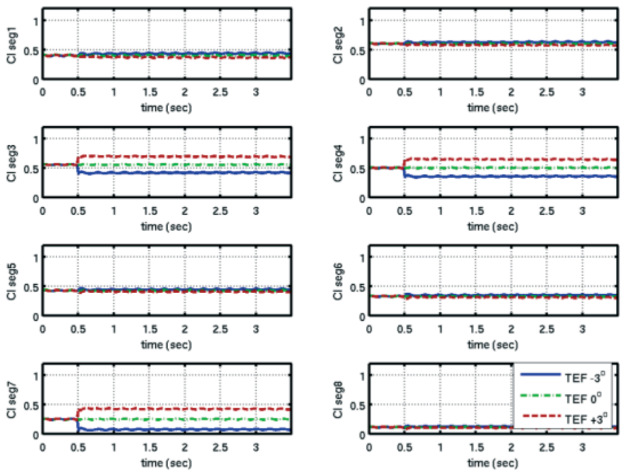

Figure 6: RGR model: Blade 1 inboard & outboard TEFs hardover

2.4 RGR Model Handling Qualities

To determine the effect of the TEF failure, it is critical to ensure that the RGR model Handling Qualities (HQs) in the unfailed state are sufficiently good that they do not mask any HQ changes caused by TEF failures. Initial handling qualities assessments showed the bare-airframe to have a large yaw from collective coupling which dominates the low speed failure analysis as demonstrated by the ADS-33E-PRF[6] criteria illustrated in Figure 8 and the response illustrated in Figure 7.

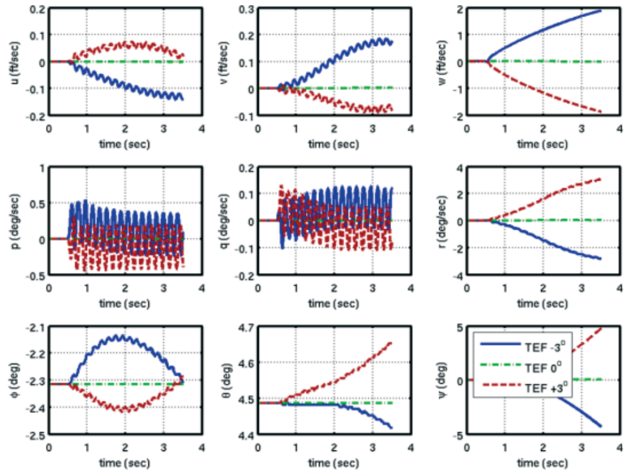

Figure 7: RGR model response to Blade 1 inboard & outboard TEFs hardover

To compensate for this, yaw rate feedback of 0.1 deg/(deg/sec) was applied. The same amount of rate feedback was also applied to the pitch and roll axes to further stabilise the aircraft longitudinal and lateral phugoid modes illustrated in Figure 9 and to reduce the roll from pitch cross coupling illustrated in Figure 10.

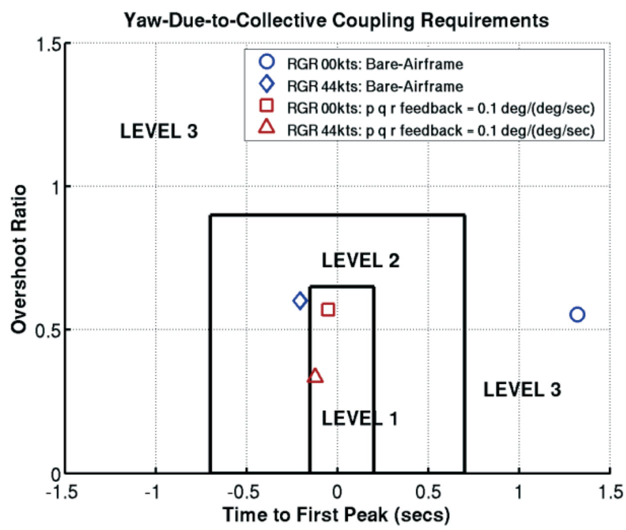

Figure 8: ADS-33E-PRF section 3.3.9.1: Yaw from collective coupling

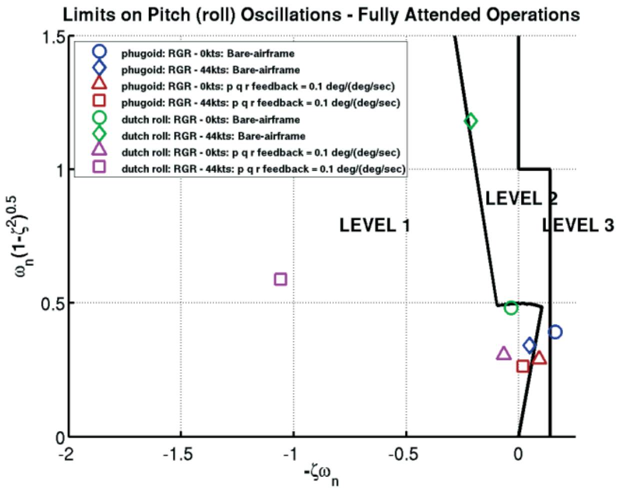

Figure 9: ADS-33E-PRF section 3.3.5.2: Stability

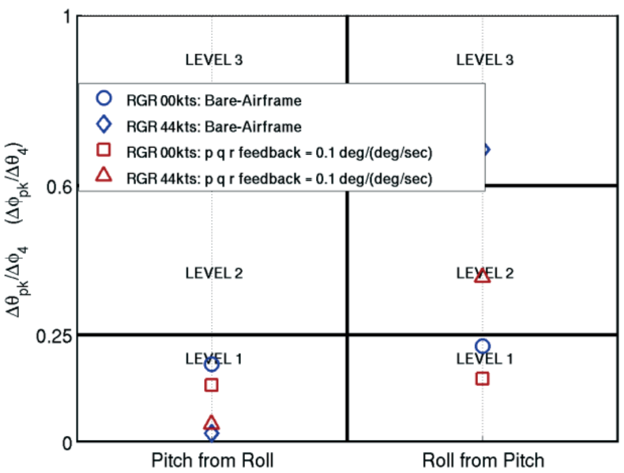

Figure 10: ADS-33E-PRF section 3.3.9.2: Pitch (Roll) from Roll (Pitch)

A summary of hover-and-low-speed HQs is provided in Table 3 showing the bare-airframe HQs to be Level 3 (phugoid mode) while the augmented RGR HQs are Level 2 overall due to Level 2 yaw quickness in the hover and Level 2 roll from pitch at 44kts. The remaining HQs are all Level 1 for the augmented airframe.

3 Failure Hazard Analysis: Results and Discussion

In the event of a malfunction failure, there is a need to know the maximum tolerable transient of the failed control surface. Two types of malfunction are considered in this paper – hardover and 1/rev malfunctions. Slowovers have not been considered as hardover malfunctions create greater angular rates and therefore cause more severe failure transients than slowover failures. Furthermore, the operating frequency of the TEFs is expected to be up to n/rev, where n is the number of blades. The worst case degraded failure is expected to be the 1/rev failure case which gives rise to pitching and rolling moments and will be assessed as a TEF 1/rev malfunction. Other degraded actuation frequencies have not been assessed in this short study. Finally a loss of function is not considered further as it is deemed to be a less severe failure than a hardover malfunction as the hardover case considers the TEF transitioning at maximum actuation rate to maximum deflection and freezing at that position (worst case loss of function is when the actuator freezes when it is already at maximum displacement – no hardover transient).

Table 3: Summary of bare-airframe and augmented RGR Handling Qualities Levels

Augmentation		Bare-airframe-RGR		Augmented-RGR	
speed		0 knots	44 knots	0 knots	44 knots
Bandwidth	Roll	1	1	1	1
	Pitch	2	1	1	1
	Yaw	2	2	1	1
Quickness	Roll	1	1	1	1
	Pitch	1	1	1	1
	Yaw	2	1	2	1
Control power	Roll	1	1	1	1
	Pitch	1	1	1	1
	Yaw	1	1	1	1
stability	Dutch Roll	1	1	1	1
	Phugoid	3	2	1	1
Interaxis coupling	Yaw from coll.	3	2	1	1
	Pitch from roll	1	1	1	1
	Roll from pitch	1	3	1	2

The failure analysis was performed with mean TEF settings of 0° and 4°, at four speeds derived from the advance ratio:

- Advance ratio 0.0 = hover
- Advance ratio 0.1 = 44 knots
- Advance ratio 0.2 = 88 knots
- Advance ratio 0.3 = 132 knots

3.1.1 Hardover failure methodology

As there are four rotor blades with two TEFs on each blade (eight TEFs), which can function correctly or fail in an up or down position, there are 3^8 (6561) possible failure combinations. To determine the worst case hardover failures for further assessment and which axis is affected by the failure, the deviation from trim roll, pitch and heading was found three seconds after the failure occurring for all possible hardover failure combinations in accordance with Table 2. In the FHA discussion case 1 refers to all TEFs failed in the up position and case 6561 when all TEFs failed in the down position. The case numbers in between represent all other failure combinations (up, down or no fail for each TEF).

3.1.2 Oscillatory Malfunction failure methodology

The second malfunction failure type considered is the 1/rev flapping. The worst cases envisaged are when the failure causes the advancing blade TEF to reach maximum deflection giving rise to a dominant pitch response and, secondly, when the forward blade TEF is maximum, giving a dominant roll response. These 1/rev failure cases are denoted as 1/rev-pitch and 1/rev-roll for the remainder of the discussion.

In the FHA discussion case 0 refers to all TEFs function correctly and case 256 refers to all TEFs suffering a 1/rev failure.

3.2 TEF 0^o setting : Hardover failure

Figure 11 shows the failure transients of the bare-airframe RGR model in hover when no recovery action is taken for 3 seconds after any of the failure combinations previously defined. It can be seen that there is little change in roll or pitch, however, as the amount of lift produced by the main rotor changes after the failure, the tail rotor balance is disturbed causing a yaw transient which is largest for cases 1 and 6561 (all TEFs failed down and all TEFs failed up).

The analysis was performed at advance ratios up to 0.3 Figure 12 shows the worst case roll, pitch and yaw failure transients from these analyses, where roll and pitch transients remain within the Level 1 region after a hardover failure throughout the flight envelope, while the yaw transient improves from Level 2 in the hover to Level 1 in the forward flight regime. Therefore, the worst RGR bare-airframe TEF hardover failure transient is the yaw transient in hover.

The corresponding rotor hub loads for the worst case failure (shown in Figure 12 to be in the hover) can be seen in Figure 13, where the hub loads and the aircraft response shown in Figure 14 generated from the failure can be equated to those from a small collective input, less than 0.7^o collective blade pitch.

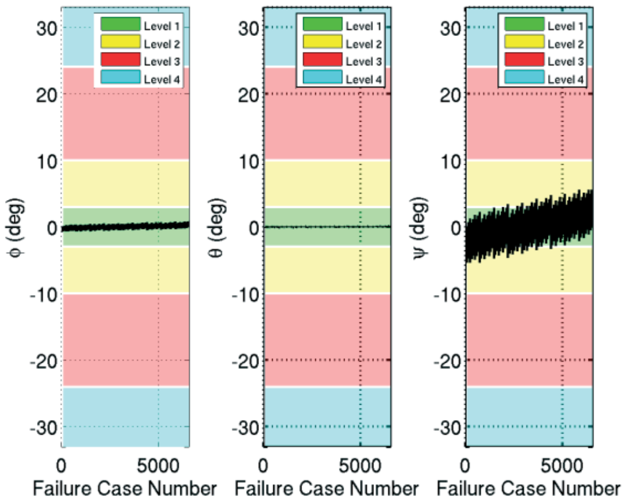

Figure 11: (TEF 0^o setting) roll, pitch and yaw attitude changes 3 seconds after hardover failure from each failure case in hover

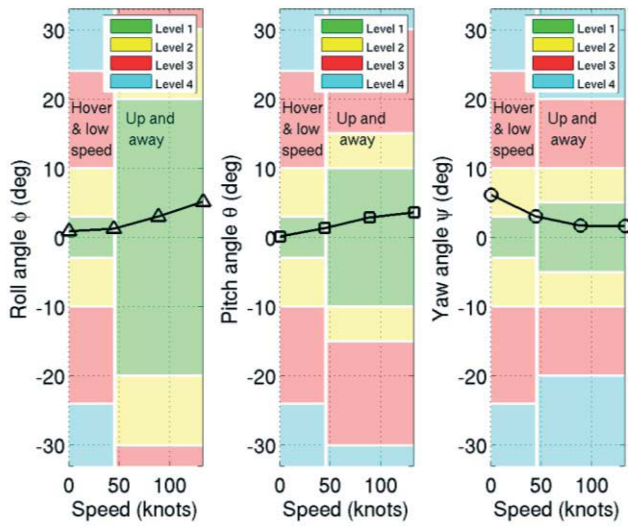

Figure 12: (TEF 0^o setting) maximum roll, pitch and yaw attitude changes 3 seconds after worst case Hardover failures across the flight speed envelope (all TEFs hardover)

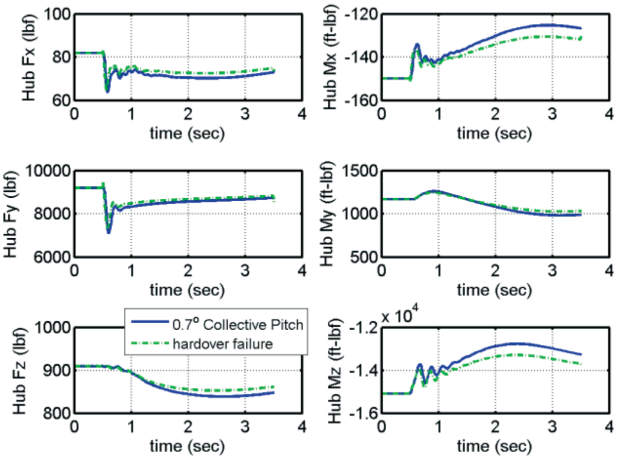

Figure 13: (TEF 0° setting) Augmented-airframe rotor hub loads in hover (all TEFs hardover)

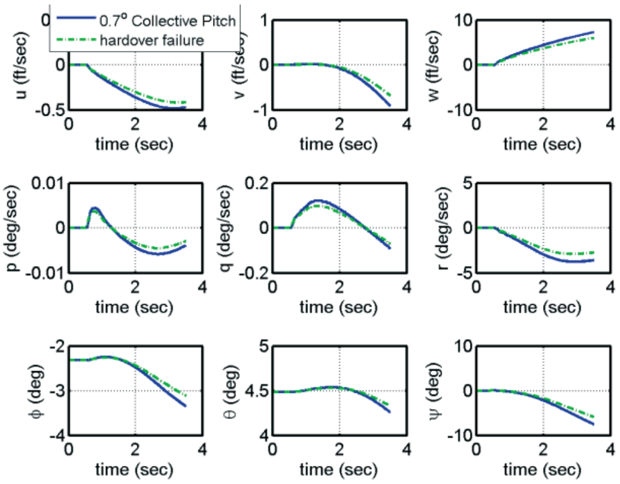

Figure 14: (TEF 0° setting) Augmented-airframe response to failure(all TEFs hardover) and 0.7° collective blade pitch in hover

3.3 TEF 0° setting : 1/rev-pitch malfunction

Figure 15 shows the 1/rev-pitch failure transients of the bare-airframe RGR model in hover when no recovery action is taken for 3 seconds after any of the failure combinations defined. The roll and yaw transients remain Level 1 while pitch was found to be Level 2. The largest pitch transient was found to be for case 256 (all TEFs 1/rev-pitch malfunction).

The analysis was performed at advance ratios up to 0.3 and the failure in hover failure was again found to be the most severe. Figure 16 shows that all worst case failure transients from these analyses remain in Level 1 except for low speed pitch which is Level 2.

The corresponding rotor hub loads for the worst case failure (shown in Figure 16 to be in the hover) can be seen in Figure 17, where the hub loads and the aircraft response shown in Figure 18 generated from the failure can be equated to those from approximately a 1° longitudinal cyclic blade pitch input.

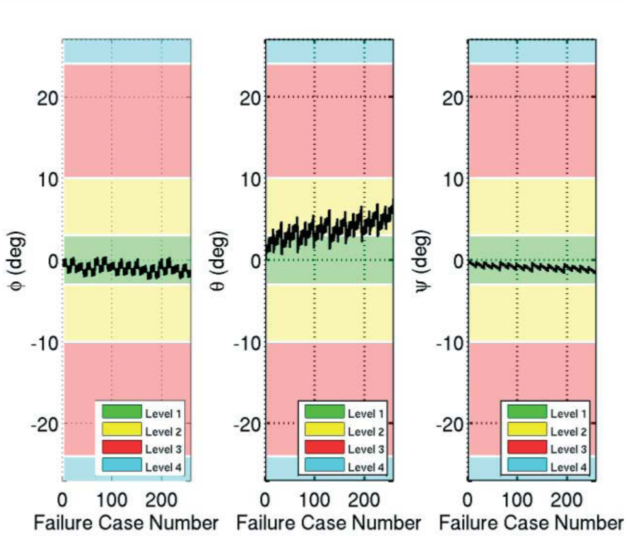

Figure 15: (TEF 0° setting) roll, pitch and yaw attitude changes 3 seconds after 1/rev-pitch malfunction failures from each failure case in hover

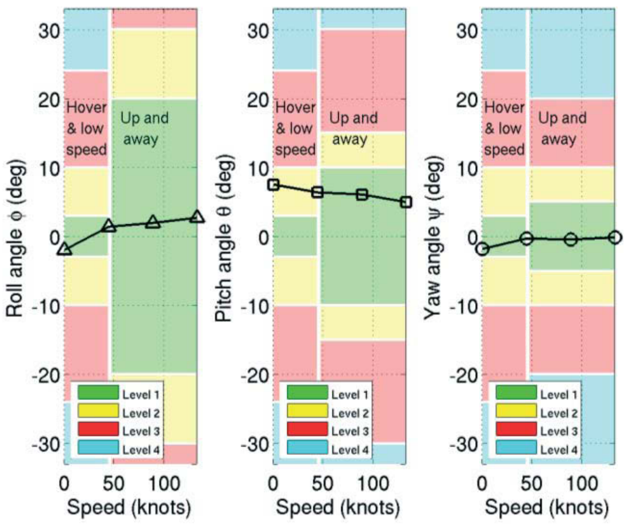

Figure 16: (TEF 0° setting) maximum roll, pitch and yaw attitude changes 3 seconds after worst case 1/rev-pitch malfunction failures across the flight speed envelope (all TEFs malfunction)

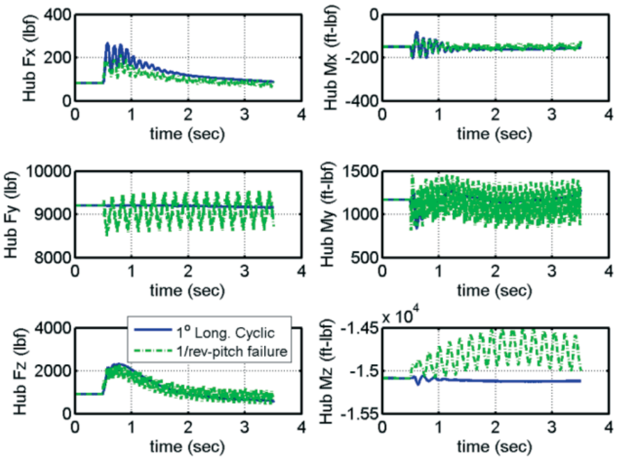

Figure 17: (TEF 0° setting) Augmented-airframe rotor hub loads in hover after worst case 1-per-rev-pitch malfunction failures (all TEFs malfunction)

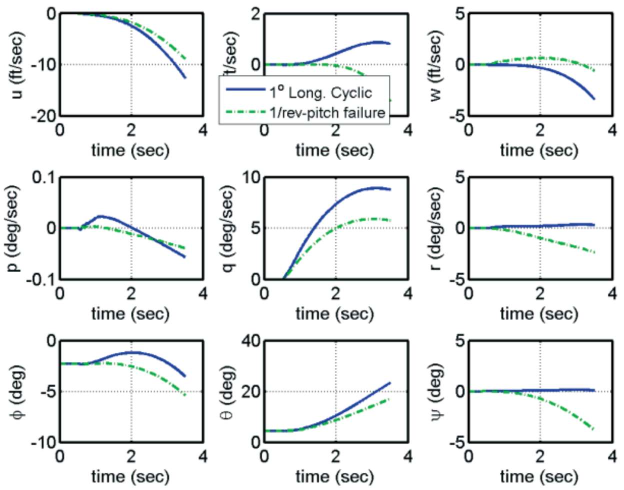

Figure 18: (TEF 0° setting) Augmented-airframe response to worst case 1-per-rev-pitch malfunction failures (all TEFs malfunction) and 1° longitudinal cyclic blade pitch in hover

3.4 TEF 0° setting : 1/rev-roll malfunction

Figure 19 shows the 1/rev-roll failure transients of the augmented model at 44 knots when no recovery action is taken for 3 seconds after any of the failure combinations. The pitch and yaw transients remain well within Level 1. In roll, the majority of failure cases show Level 2 failures. However, if all TEFs suffer a 1/rev-roll failure at the same time, Level 3 HQs are reached.

Figure 20 shows that the worst case pitch and yaw transients from these analyses remain within Level 1 throughout the flight envelope. Roll in forward flight is Level 1, Level 2 in the hover but Level 3 in the upper speed region of the hover-and-low-speed flight regime.

The corresponding rotor hub loads for the worst case failure (shown in Figure 20 to be at 44 knots) can be seen in Figure 21, where the hub loads and the aircraft response shown in Figure 22 generated from the failure can be equated to those from approximately a 1° lateral cyclic pitch.

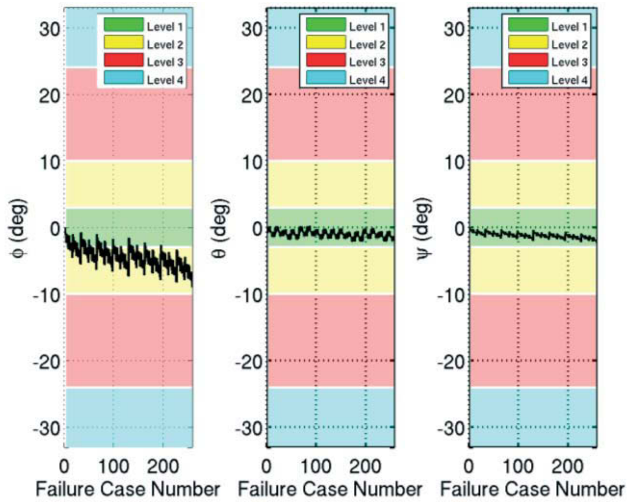

Figure 19: (TEF 0° setting) roll, pitch and yaw attitude changes 3 seconds after 1/rev-roll malfunction failures from each failure case in hover

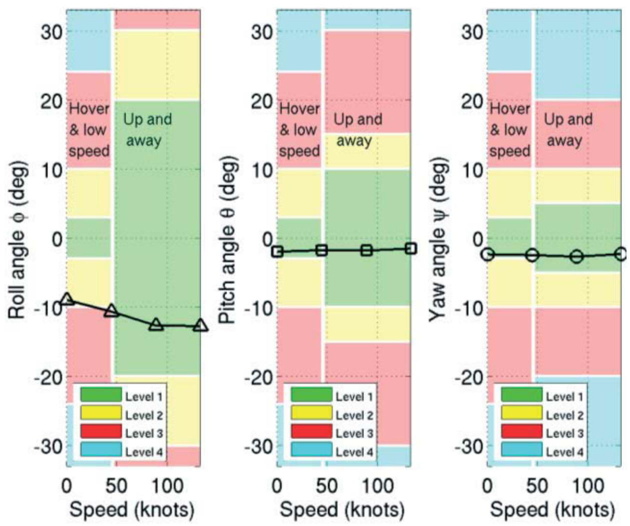

Figure 20: (TEF 0° setting) maximum roll, pitch and yaw attitude changes 3 seconds after worst case 1/rev-roll malfunction failures across the flight speed envelope (all TEFs malfunction)

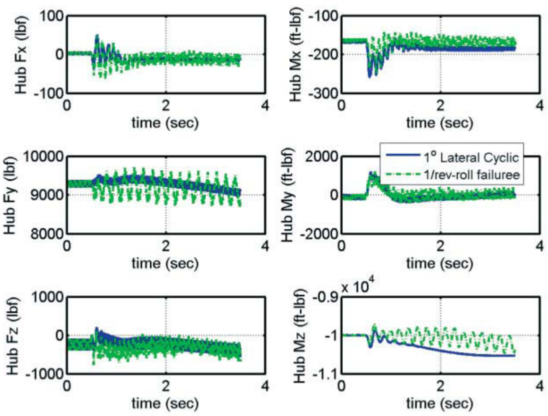

Figure 21: (TEF 0° setting) Augmented-airframe rotor hub loads in hover after worst case 1-per-rev-roll malfunction failures (all TEFs malfunction)

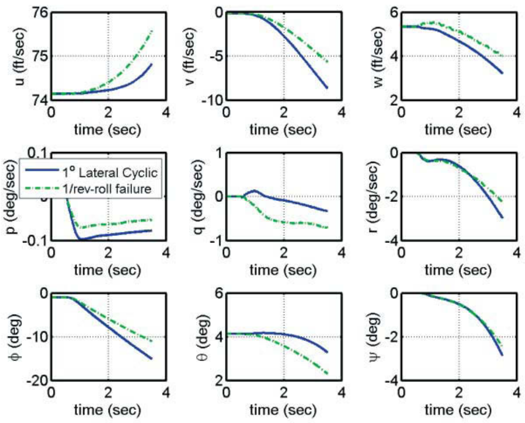

Figure 22: (TEF 0° setting) Augmented-airframe response to worst case 1-per-rev-roll malfunction failures (all TEFs malfunction) and 1° lateral cyclic pitch at 44kts

3.5 TEF 0° setting: Loss of Function Failures

From the hardover malfunction failure analysis, the worst case failure was predicted to be all TEFs fail up/down simultaneously. Trim sweeps were performed across the flight envelope to determine how much additional control was required to compensate for the ΔC_L generated by the failed TEFs. Figure 23 shows that as all TEFs fail up/down, only a change in collective lever (Xc) of approximately 0.3 inches (giving an additional 0.7° collective blade pitch) is required to compensate for the change in ΔC_L from the TEF failure showing good agreement with the collective required to generate similar rotor hob loads and aircraft response as the worst hardover failure case.

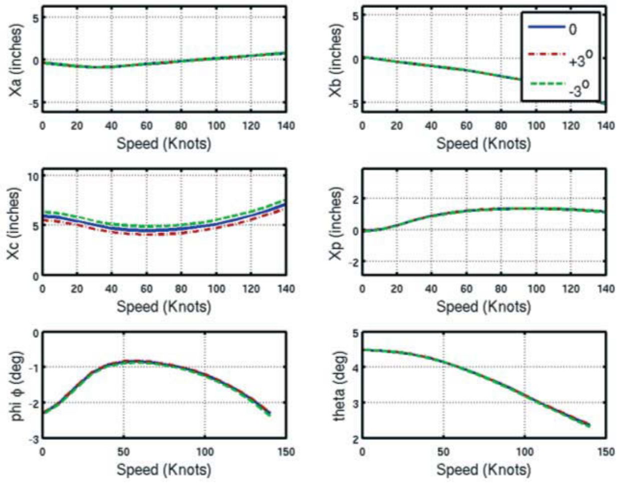

Figure 23: (TEF 0° setting) Trimsweep comparison of RGR model with no hardover failure and ±3° hardover failures

4 TEF 4° setting: Failure analysis

In addition to considering the TEF having an initial deflection of 0°, it is possible to use the NACA0012 aerofoil and TEF to provide insight into the TEF failure effect on a cambered aerofoil. Therefore for the FMEA, the TEF initial setting could be considered to be 4°. The FMAE is again conducted to determine the effect of the change in TEF default setting. In addition, from the 0° TEF setting, the 1/rev-pitch/roll malfunctions are more severe failures than the hardover malfunction. Therefore, only the 1/rev failures have been examined for the 4° TEF setting.

4.1 TEF 4° setting: 1/rev-pitch malfunction

The analysis was again performed at aspect ratios up to and including 0.3. Figure 24 shows the 1/rev-pitch failure transients of the augmented RGR model in hover when no recovery action is taken for 3 seconds after any of the failure combinations. Roll and yaw transients remain well within Level 1 for all 1/rev-pitch malfunctions, while pitch transients are Level 2 for most failure combinations. The worst pitch transient failure case is again case 256 (all TEFs 1/rev-pitch malfunction).

Figure 25 shows that roll and yaw transients are Level 1 throughout the flight envelope, while pitch transients improve from Level 2 in low speed to Level 1 in forward flight. The 4° TEF setting can also be seen to have slightly smaller failure transient attitude displacements than for the 0° TEF malfunction (Figure 15 and Figure 16) due to the TEF producing a smaller ΔC_L (from Figure 2) when deflected to 7°.

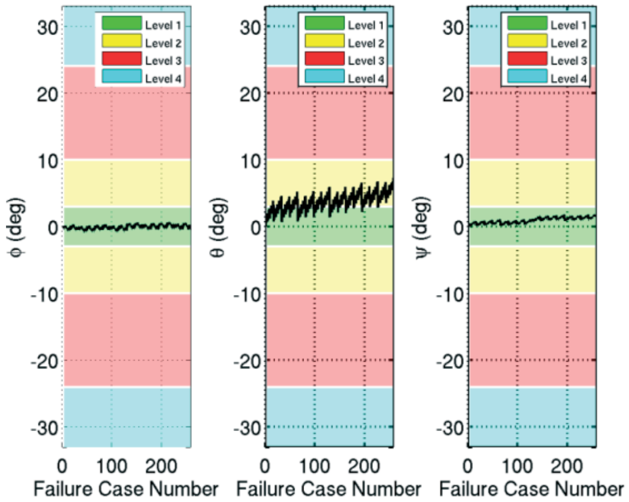

Figure 24: (TEF 4° setting) roll, pitch and yaw attitude changes 3 seconds after 1/rev-pitch malfunction failures from each failure case in hover

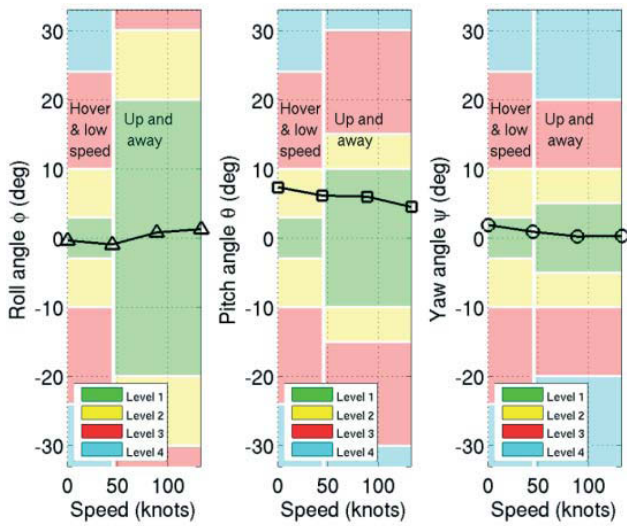

Figure 25: (TEF 4° setting) maximum roll, pitch and yaw attitude changes 3 seconds after worst case 1/rev-pitch malfunction failures across the flight speed envelope (all TEFs malfunction)

4.2 TEF 4° setting: 1/rev-roll malfunction

Figure 26 shows the 1/rev-roll failure transients of the augmented-airframe RGR model at 44 knots when no recovery action is taken for 3 seconds after any of the failure combinations defined. Pitch and yaw transients remain well within Level 1 for all 1/rev-pitch malfunctions, while the augmentation has improved the 1/rev-roll transient from Level 3 on the bare-airframe to Level 2. The worst roll transient failure case is again case 256 (all TEFs 1/rev-pitch malfunction).

The analysis was repeated at advance ratios up to 0.3 and the worst case results shown in Figure 27. Pitch and yaw transients are Level 1 throughout the flight envelope after TEF failures, while roll is Level 1 in forward flight and Level 2 for low speed. The 4° TEF setting can also be seen to have slightly smaller failure transient attitude displacements than the 0° TEF malfunction (Figure 19 and Figure 20), again due to the TEF producing a smaller ΔC_L (from Figure 2) when deflected to 7°.

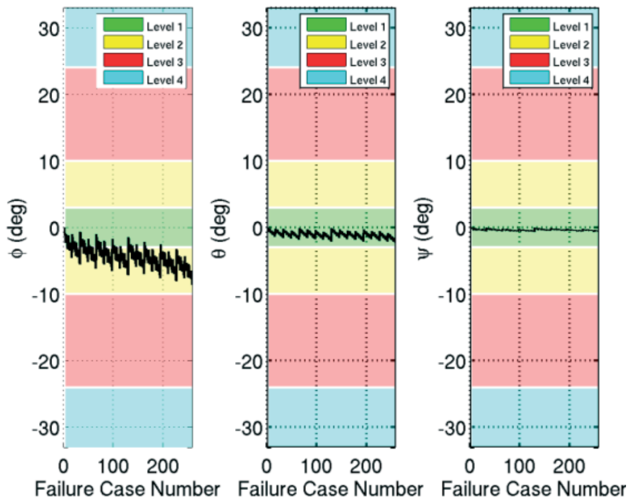

Figure 26: (TEF 4° setting) roll, pitch and yaw changes 3 seconds after 1/rev-roll malfunction failures from each failure case at 44 knots

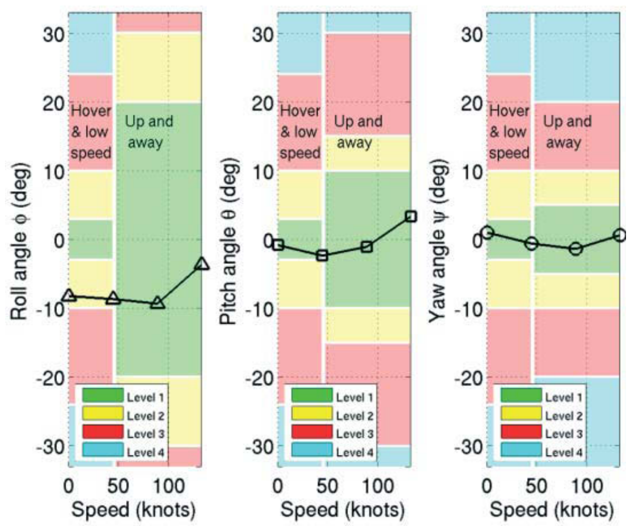

Figure 27: (TEF 4^o setting) maximum roll, pitch and yaw attitude changes 3 seconds after 1/rev-roll fail

4.3 Summary of Divided Attention Failure Analysis

A summary of worst case hardover malfunction transient response HQ Levels are listed in Table 4, worst case 1/rev-pitch malfunction in Table 5 and finally worst case 1/rev-roll in Table 6. Divided attention results show the hardover malfunction failure is not as severe a failure as the 1/rev-pitch/roll malfunction. Turning to the 1/rev malfunctions, Table 6 shows the 1/rev-roll transient Levels to be worse than the 1/rev-pitch transients in Table 5 at low speed, where one Level 3 rating is seen with the augmented aircraft at a speed of 44 knots. Changing the TEF setting to 4^o reduces the effect of the TEF failure due to the TEF producing a smaller ΔC_L (from Figure 2) when deflected to 7^o. In forward flight, all failure transients were found to remain within Level 1.

Table 4: Summary of worst case hardover Failure Transient Level for 0^o and TEF settings

BARE-AIRFRAME			Speed	AUGMENTED-AIRFRAME		
Roll	Pitch	yaw		Roll	Pitch	yaw
1	1	2	0	1	1	2
1	1	1	44	1	1	1
1	1	1	88	1	1	1
1	1	1	132	1	1	1

Table 5: Summary of worst case 1/rev-pitch Failure Transient Level for 0^o and 4^o TEF settings

BARE-AIRFRAME						Speed	AUGMENTED-AIRFRAME					
Roll		Pitch		yaw			Roll		Pitch		yaw	
0^o	4^o	0^o	4^o	0^o	4^o		0^o	4^o	0^o	4^o	0^o	4^o
2	2	3	2	2	2	0	1	1	2	2	1	1
1	2	2	2	1	1	44	1	1	2	2	1	1
1	1	1	1	1	1	88	1	1	1	1	1	1
1	1	1	1	1	1	132	1	1	1	1	1	1

Table 6: Summary of worst case 1/rev-roll Failure Transient Level for 0^o and 4^o TEF settings

BARE-AIRFRAME						Speed	AUGMENTED-AIRFRAME					
Roll		Pitch		yaw			Roll		Pitch		yaw	
0^o	4^o	0^o	4^o	0^o	4^o		0^o	4^o	0^o	4^o	0^o	4^o
3	3	2	2	2	1	0	2	2	1	1	1	1
3	3	2	1	2	1	44	3	2	1	1	1	1
2	1	1	1	2	1	88	1	1	1	1	1	1
2	1	1	1	2	1	132	1	1	1	1	1	1

5 Piloted Simulation Analysis

The Flight simulator used in this analysis was the newly installed HELIFLIGHT-R simulator at the University of Liverpool[9] shown in Figure 28. HELIFLIGHT-R is a PC-based re-configurable flight simulator constructed as a twelve foot diameter dome where three high definition projectors with additional automatic edge blending and geometry correction to generate the 220x70 degree field of view. The HELIFLIGHT-R features a six-axis degree of freedom, electrically actuated motion platform, a 2 pilot crew station is equipped with a 4-axis (longitudinal and lateral cyclic, collective and pedals) control loading system that back-drives the pilots' controls and allows fully programmable force-feel characteristics. The dome is also equipped with an Instructor Station which can, for fixed-base operation, control all simulator functionality.

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.

Figure 28 The University of Liverpool 'HELIFLIGHT-R' Flight Simulator & Cockpit View

In addition to determining the effect of the failure transient in terms of attitude change in a defined time frame to simulate divided attention, 'fully attended' pilot-in-the-loop simulation analysis of the malfunction failures was carried out at the University of Liverpool's HELIFLIGHT-R simulation facility to investigate the change, if any, in HQs following the failure. Based upon the preceding analysis, two Mission Task Elements (MTEs) were selected for testing. The bob-up was selected as the hover MTE and the roll-step at 44 knots. Higher speeds were not tested as the worst case augmented RGR malfunction failures were identified as being at the lower speeds.

At the end of each MTE, the simulator was paused and the pilot asked to complete an 'in-cockpit pilot questionnaire'. The pilot questionnaire serves two purposes, the first is to help the pilot assess performance during the manoeuvre and return a Handling Qualities Rating from the Cooper-Harper Handling Qualities rating[12] and to help the flight test engineers managing the simulation trial, document performance and note any handling qualities issues identified by the pilot.

5.1 Bob-Up MTE

The bob-up task is based on the ADS-33E-PRF[6] task and is performed 150ft in front of a hover board 8ft high and 12ft wide with a marked inner rectangle 4ft high and 6ft wide as illustrated in Figure 29, situated at the end of a runway providing additional lateral visual cues. Between and equidistant from the hover board and aircraft is a pole with a sphere on the top. The task begins from a stabilised hover at 30ft, the pilot then climbs and stabilises with the sphere inside the inner box for desired performance or within the remainder of the hover board for adequate performance. The task aggression level is defined by a torque increase of 10%. The pilot was also requested to maintain the input for as long as possible during the task to make the hover capture as aggressive as possible whilst meeting the performance targets stated in Table 7.

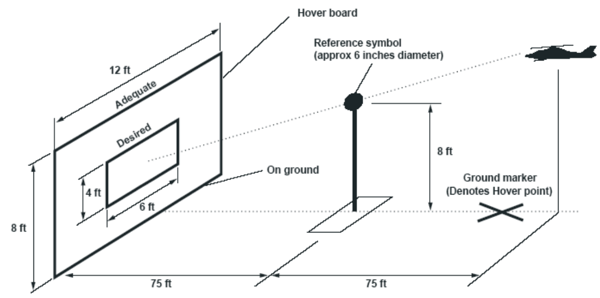

Figure 29: Bob-up MTE

Table 7: Bob-Up Performance Requirements

	Desired	Adequate
Maintain finish altitude within $\pm X$ft	3ft	6ft
Maintain heading within $\pm X^o$	3^o	6^o
Maintain longitudinal/lateral position within $\pm X$ft	6ft	10ft

Time histories with the augmented-RGR model performing the bob-up MTE, with and without malfunction failures were recorded and can be viewed in Figure 30. The pilot commented that the RGR model had poor damping in roll and yaw and also a yaw-from-collective couple, which resulted in an HQR 4 for the no failure case. A hardover failure on all TEFs was next introduced during the manoeuvre after the pilot had initiated the climb. The pilot commented that when the failure was implemented, the climb rate increased and collective had to be lowered slightly to maintain the desired climb rate. However this did not impact upon the task performance and the pilot stated that it felt similar to a vertical gust. Next the 1/rev-pitch and 1/rev-roll malfunction failures were introduced and again, as the task was being flown as a 'fully attended' task, the transients were not allowed to develop and the pilot reported no adverse HQs, again returning HQR 4.

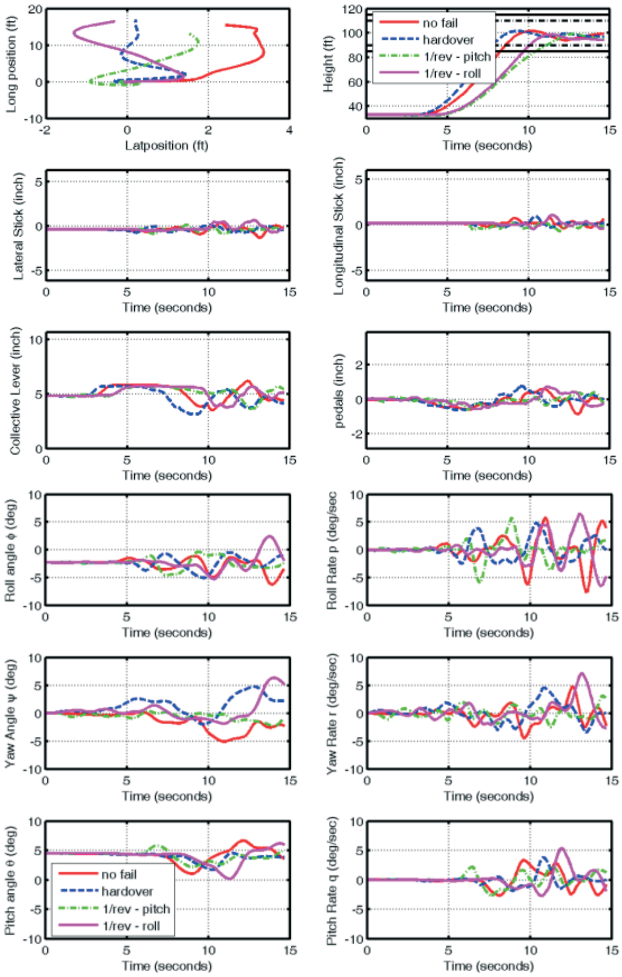

Figure 30: Bob-Up time histories for TEF malfunction failures

5.2 Roll-Step

The roll-step[13] depicted in Figure 31 is flown mainly with reference to outside world cues. Both sides of a runway are flanked by an ordered series of numbered gates 500ft apart where the pilot is required to fly through a defined series of these gates that form the roll-step task. Before the task begins, the pilot is required to be aligned with the runway left edge, flying at a reference height and speed. Once the specified starting point (or gate number) is reached, the pilot initiates the task by rolling to the right across the runway then attempts to bring the aircraft back within the required performance standards on reaching the designated gate on the right runway edge. 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 specified gate. When passing through each of these gates, the pilot must meet a set of performance criteria listed in Table 8. Finally a stabilisation period of 1000ft included as an integral part of the task in which the pilot must maintain the required performance criteria. The task is performed at 44 knots where the pilot is asked to realign with the far side of the runway within 1000ft of initiating the task.

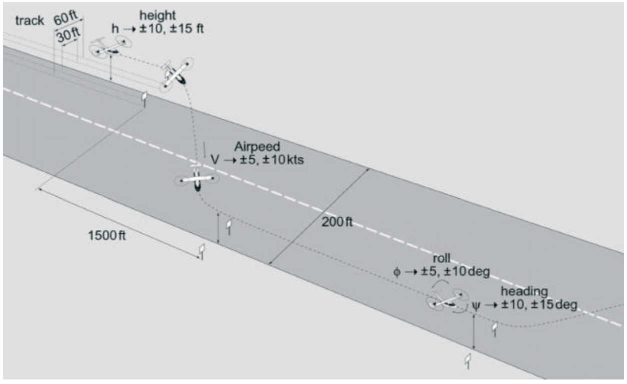

Figure 31 Roll-Step MTE

Table 8: Roll-Step Performance Requirements

	Desired	Adequate
Maintain speed throughout the MTE within $\pm X$ knots	5kts	10kts
Maintain altitude throughout the MTE within $\pm X$ feet	10ft	15ft
Maintain heading when passing through the gates within $\pm X^{o}$	10^{o}	15^{o}
Maintain bank angle when passing through the gates within $\pm X^{o}$	5^{o}	10^{o}

The roll-step was first performed with the RGR model at 44 knots with no TEF failures and the time histories documented in Figure 32. The pilot had no adverse comments about the aircraft HQs and easily met desired performance requirements, returning an HQR 2. When the worst case hardover predicted from the previous analysis (all TEFS on all rotor blades) was applied, the pilot reported only small disturbances in flightpath, akin to light turbulence, which had little impact on his ability to complete the MTE, again returning HQR 2. 1/rev-pitch and roll flapping was next introduced and again HQR 2s were returned. The pilot again cited only small but easily recoverable flightpath excursions during the 'fully attended' MTEs.

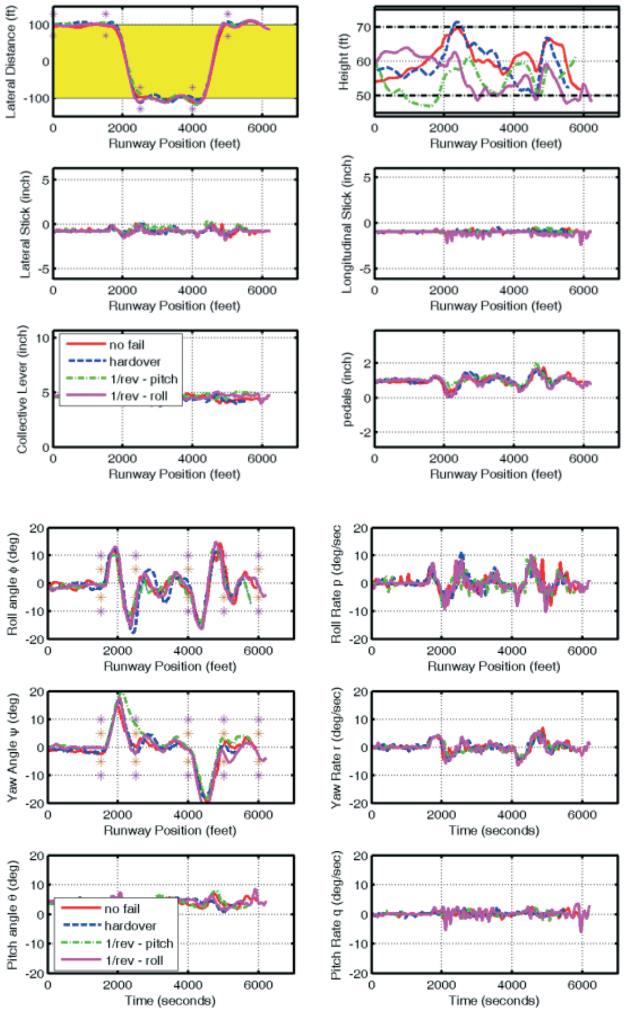

Figure 32: Roll-Step at 44kts: time histories for TEF malfunction failures

6 Summary & Conclusions

A Failure Modes and Effects Analysis (FMEA) has been carried out on the FLIGHTLAB RGR model with two TEFs on each rotor blade with mean settings of 0^o and 4^o, to assess the impact of TEF failures on handling qualities. Failure transient handling qualities Levels were defined in terms of attitude displacements within three seconds of the failure and determined for a range of TEF malfunction failure types.

The hardover malfunction failure is not as severe a failure as the 1/rev-pitch/roll malfunction for TEF 0^o setting. The 1/rev malfunctions, the 1/rev-roll transient Levels were found to be worse than the 1/rev-pitch transients at low speed, where one Level 3 response was found. Changing the TEF setting to 4^o reduces the effect of the TEF failure due to the TEF producing a smaller ΔC_L when deflected to 7^o. In forward flight, all failure transients were found to remain within Level 1.

Rotor hub loads generated from the failures and the aircraft response to the failures are shown to be similar in effect to a 0.7 degree collective input for a hardover failure, and 1 degree longitudinal and lateral cyclic for 1-per-rev pitch and roll failures respectively.

Piloted simulation assessment of the TEF malfunction failures concluded that the worst case TEF failures had little impact on the pilot's ability to complete a task, when the pilot was fully attended. Even when the failure transient was left to develop for three seconds, control of the aircraft was regained with little increase in workload.

This short study only considered the change in lift from the trailing edge flap failure. However, as the TEF moves, torsional bending effects will have effects on the response and should be considered further.

7 Acknowledgements

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