UNIFIED TILT ROTOR HANDLING QUALITIES; FEASIBLE OR IMPRACTICABLE?

PART I: SETTING THE CHALLENGE

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ABSTRACT. We investigate the feasibility of conferring on all members of a ‘family’ of civil tilt rotor aircraft identical (or at least similar) Level 1 handling qualities. This would allow pilots to convert between aircraft with minimal training. This paper presents a study of predicted and assigned ‘bare-airframe’ handling qualities in helicopter mode, based on the rotorcraft design specification ADS-33E-PRF, for a family of three tilt rotor aircraft ranging from 6 to 15 tonnes. Although the aircraft vary widely in weight and geometry, predicted lateral axis handling qualities were found to be similar for all aircraft: predominantly on the Level 2/3 boundary for the ‘all other MTEs’ category, and Level 3 for ‘target acquisition and tracking’ requirements category. In the pitch and yaw axes, more significant variations in predicted handling qualities were found. The assigned handling qualities analysis leads to results from four search and rescue mission oriented tasks, showing generally good agreement with the predicted analysis. The challenges in unifying the handling qualities within the Level 1 region are highlighted. A second, complementary, paper will present practical solutions to the unification problem, based on control system design concepts.

1. INTRODUCTION

Handling qualities (HQs) are a system-level design attribute stemming from the integration of a range of different vehicle technologies. Future rotorcraft should be designed to meet the safety and performance standards reflected in Level 1 HQs throughout the operational flight envelope. What constitutes Level 1 HQs depends on the mission, particularly when it comes to levels of agility. Typically one would expect large aircraft to be less agile, although the philosophy of ADS-33 makes it clear that HQs are mission-oriented, not size oriented. However, tilt rotor aircraft operations with different payload requirements could be streamlined with commonality between the HQs of different aircraft sizes. As such, it is considered desirable for all members of a ‘family’ of civil tilt rotor (CTR) aircraft to possess similar if not identical Level 1 handling qualities, allowing pilots to convert between aircraft with minimal training.

In this, the first of two papers, the challenges in unifying tilt rotor HQs are laid out, while a second paper [1] presents practical solutions to control system concepts that effectively unify the HQs for a ‘family’ of tilt rotor aircraft; the aircraft considered range from small (5-7 tonnes, CTR-S) to medium (10-12 tonnes, CTR-M) and large (greater than 15 tonnes, CTR-

L). The aircraft used in this study are illustrated in Figure 1 with selected configuration data listed in Table 1, and are based upon the Bell/NASA/Army XV-15 [2] and the Eurocopter Eurotilt and EuroFAR concepts [3, 4], which were developed into FLIGHTLAB simulation models by the Flight Science and Technology research group (FS&T) at the University of Liverpool (UoL). The papers are the latest in a series from the research at Liverpool addressing the simulation modelling, handling qualities and flight control challenges on future civil tilt rotor aircraft [5-13].

Figure 1 Bell-NASA-Army XV-15 Tilt Rotor and Eurocopter Eurotilt and Eurofar tilt rotor Concepts

Table 1 Tilt Rotor Configuration Data

	CTR-S	CTR-M	CTR-L
Mass	13003lb (5897kg)	22416lb (10166kg)	33110lb (15016kg)
Rotor radius	12.5ft (3.81m)	16.4ft (4.99m)	18.4ft (5.61m)
Disc Loading	13.24lb/ft^2 (64.6kg/m^2)	13.26lb/ft^2 (64.9kg/m^2)	15.56lb/ft^2 (75.9kg/m^2)
Number of blades/rotor	3	3	4
Rotor speed (rad/sec)	59.2	43.98	39.25
Length	42ft (12.8m)	50ft (15.25m)	63.6ft (19.4m)
Wing span	32.2ft (9.815m)	41.6ft (12.68m)	48.0ft (14.63m)

1.1 Framework for HQs Analysis

The hover and low speed handling qualities presented in this paper are based on the pilot assigned and off-line predicted HQs using the mission oriented ADS-33E-PRF [14] Dynamic Response Criteria (DRC). The DRC represent the flight behaviour in response to controls and disturbances. Figure 2 illustrates the DRC in 4 groups, 2 relating to agility (large-moderate amplitude manoeuvres) and 2 relating to stability (low-high frequency modes) [15]. The criteria in ADS-33E-PRF are theoretically related for classical rate or attitude response types, so that, for example, attitude quickness tends to control power at large amplitude and bandwidth at small amplitude; the character of the higher frequency modes determines the closed-loop stability and the degree of precision achievable in tracking tasks. Control power and response time are used in the heave axis and finally criteria are described which define off-axis response to a control input or disturbance.

The mission orientation of the handling qualities requirements in [14] is partly defined by the nature of the mission task elements (MTEs) to be flown and also whether the (military) role of the vehicle is combat/attack, search and rescue (SAR) or cargo/utility. Target acquisition and tracking' phases are typified by combat scenarios while 'all other MTEs' are more relevant to cargo/utility aircraft. This raises the question - are the non-combat or 'all other MTEs' requirements of [14] appropriate for a civil rotorcraft in, say, a search and rescue role? Furthermore, if the Level 1 target acquisition and tracking requirements cannot be met, is a degradation in HQs for a small percentage of the mission scenario acceptable when the high agility tasks are being performed? This question is discussed throughout this paper and also in Reference [2].

The DRC give the predicted HQs. In the present research, the assigned HQs are delivered through piloted simulation tests using the Cooper-Harper handling qualities rating scale (Figure 3) and associated handling qualities levels [16]. The assigned and predicted HQs are then compared and any discrepancies investigated. This is an important stage in HQ quantification since it is recognised that the single axis, 2-parameter DRC cannot wholly describe the total pilot experience.

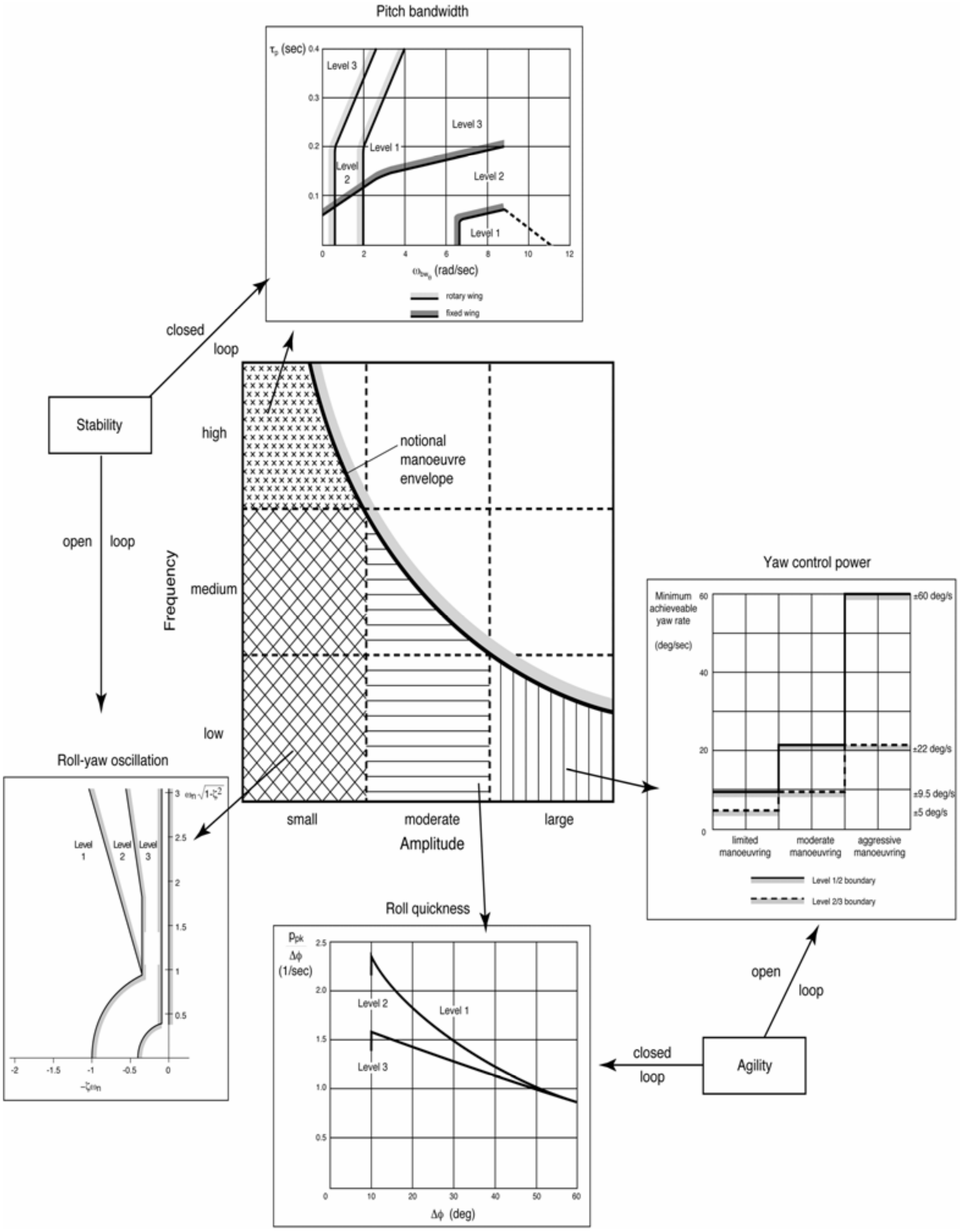

Figure 2 Dynamic Response Criteria [15]

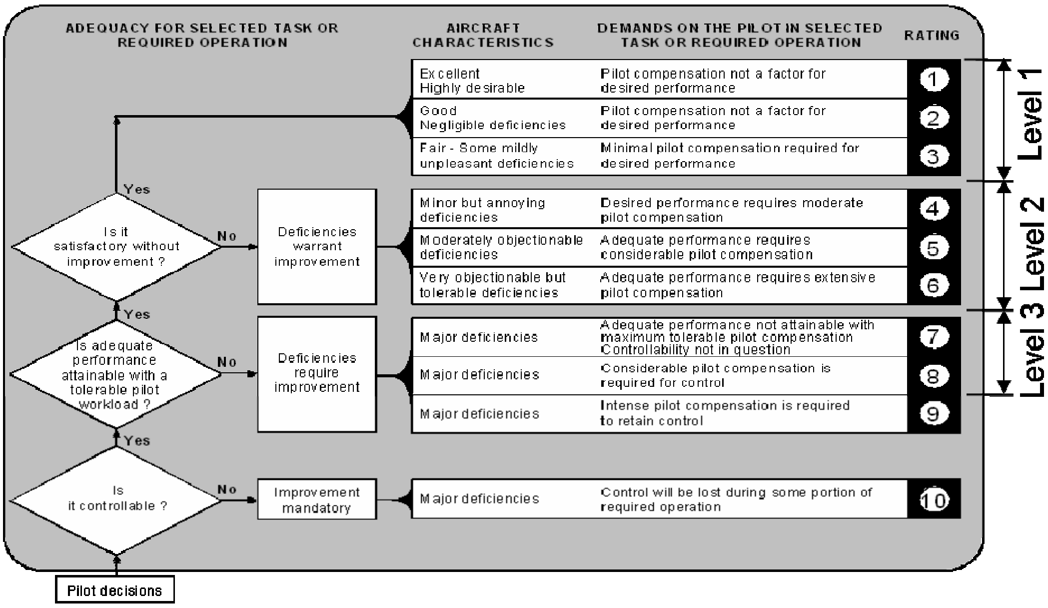

Figure 3 Cooper-Harper Handling Qualities Rating Scale

1.2 Mission Task Elements (MTEs)

The flight test manoeuvres used in the assigned HQ assessment were based on those documented in ADS-33E-PRF, where missions are synthesised into Mission Task Elements (MTEs) from which the critical HQs of the aircraft can be established, reiterating the point already made that irrespective of aircraft class or size, the key HQs issues centre on the MTEs to be flown. Furthermore, MTE handling qualities boundaries are defined in terms of the mission context. In the present study, the three aircraft are designated for a Search and Rescue (SAR) role where the helicopter MTEs were selected as Hover-turn, Pirouette, Vertical manoeuvre and the Hover (translation/reposition) task.

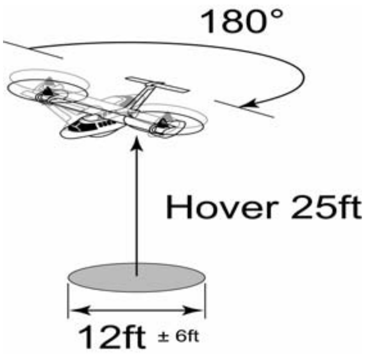

Figure 4 Hover-Turn task

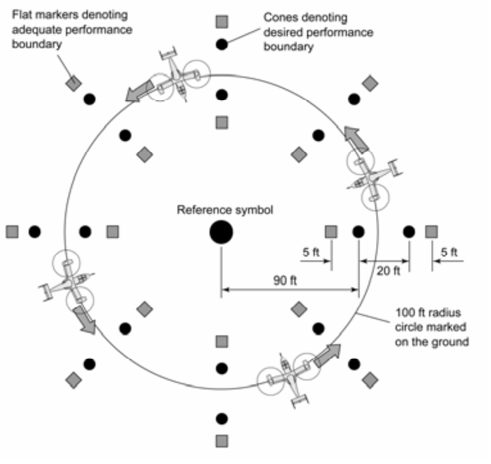

Figure 5 Pirouette MTE

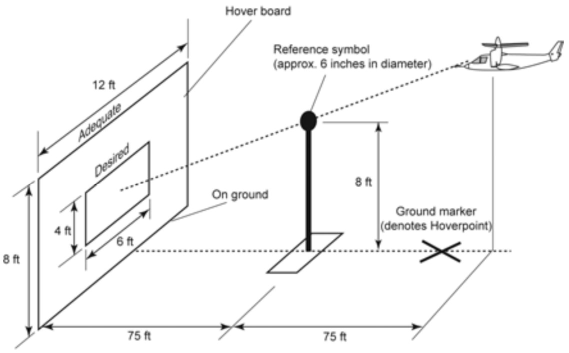

Figure 6 Vertical reposition MTE

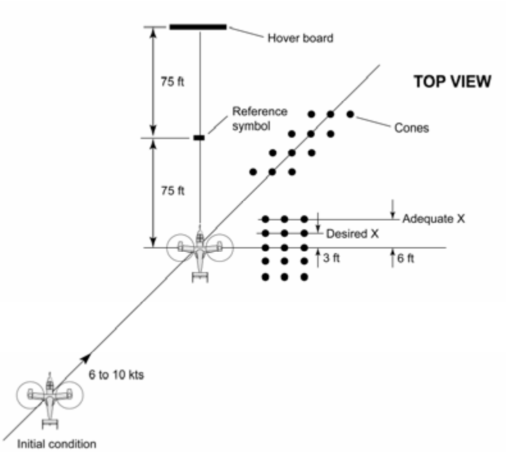

Figure 7 Hover Translation MTE

1.2.1 Hover-Turn

The hover-turn MTE was flown at a helipad, positioned at the intersection of two perpendicular taxiways, as illustrated in Figure 4. The task begins from a 25ft hover aligned with the centreline of one of the taxiways and the pilot was required to turn 180^o to the left, realigning with the centreline of the same taxiway. On completion of the turn, a stabilised hover must be maintained for 5 seconds. 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 20 seconds for a low aggression, 15 and 10 seconds for moderate and high aggression tasks respectively. This forces the pilot to apply increasingly larger and more rapid control inputs to complete the task and exposes any PIOs or cliff edges in the aircraft response. The performance targets are listed in Table 2.

Table 2 Hover-Turn Performance Requirements

	Desired	Adequate
Maintain altitude within $\pm X$ft from the ground	3ft	6ft
Stabilise the final rotorcraft heading within $\pm X^o$	3^o	6^o
Maintain longitudinal/lateral position within $\pm X$ft	3ft	6ft

1.2.2 Pirouette

The pirouette task checks the ability to accomplish precision control of the aircraft simultaneously in roll, pitch, yaw and heave. The pirouette was initiated from a stabilised hover at 15ft over a point on the circumference of a 100ft radius circle with the nose of the aircraft pointing at a pole at the centre of the circle as illustrated in Figure 5, The pilot must perform a lateral translation around the circle while keeping the aircraft pointing at the reference pole. In addition to meeting the performance criteria listed in Table 3, the pilot must maintain a selected reference point on the aircraft within ±10/15ft of the circle throughout the lateral translation around the circle. On completion of the translation around the circle, a stabilised hover should be maintained for 5 seconds.

Table 3 Pirouette Performance Requirements

	Desired	Adequate
Complete the circle and arrive back at start point within *X*secs	45sec	60sec
Maintain altitude within ±*X*ft of the ground	3ft	10ft
Maintain heading so that the nose of the aircraft points at the centre of the circle within $\pm X^o$	10^o	15^o
Stabilise the final rotorcraft heading within $\pm X^o$	3^o	6^o
Maintain longitudinal/lateral position within ±*X*ft	3ft	6ft

1.2.3 Bob-Up

The bob-up task was 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 6, 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 25ft, 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 was performed at 3 aggression levels, defined by torque increase (10, 20 and 30 % increase). The pilots were 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 4.

Table 4 Bob-Up Performance Requirements

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

1.2.4 Hover-Reposition

This task assesses the ability of the aircraft to capture a hover. The task begins by initiating a 45^o translation at a height of 25ft, reaching a groundspeed of 6 to 10 knots, towards the hover board (see previous hover board description), centred 25ft above the ground with a pole and sphere 75ft in front of the board. The task is then to capture the hover 150ft in front of the hover board, maintaining the ball within the inner box for desired performance or within the remainder of the hover board to adequate performance. Other performance criteria are listed in Table 5.

Table 5 Hover-Reposition Performance Requirements

	Desired	Adequate
Maintain finish altitude within ±*X*ft	3ft	6ft
Maintain heading within $\pm X^o$	5^o	10^o
Maintain longitudinal/lateral position within ±*X*ft	3ft	6ft

1.3 Atmospheric Disturbance

In addition to the pilots being required to complete the MTEs within specified performance limits, they were also required to perform the task with an additional disturbance in the form of pitch and roll moments simulating the combined effects of atmospheric disturbances and interactional aerodynamics. The aim of this was to ensure that the pilot was constantly closing the loop and compensating for the natural instabilities of the aircraft. The disturbance was created by summing a series of multi-phase sine waves with frequencies ranging from 1-5 radians/second. The disturbances were applied at the aircraft centre of gravity in addition to those already calculated in the aircraft model. On completion of each MTE, the flight simulation was paused and the pilot completed an in-cockpit questionnaire leading to a Handling Qualities Rating (HQR) from the Cooper-Harper rating scale (Figure 3). Before presenting the results of the handling qualities assessment, the HELIFLIGHT simulation facility at Liverpool is introduced.

1.4 The University of Liverpool’s HELIFLIGHT Flight Simulation Facility

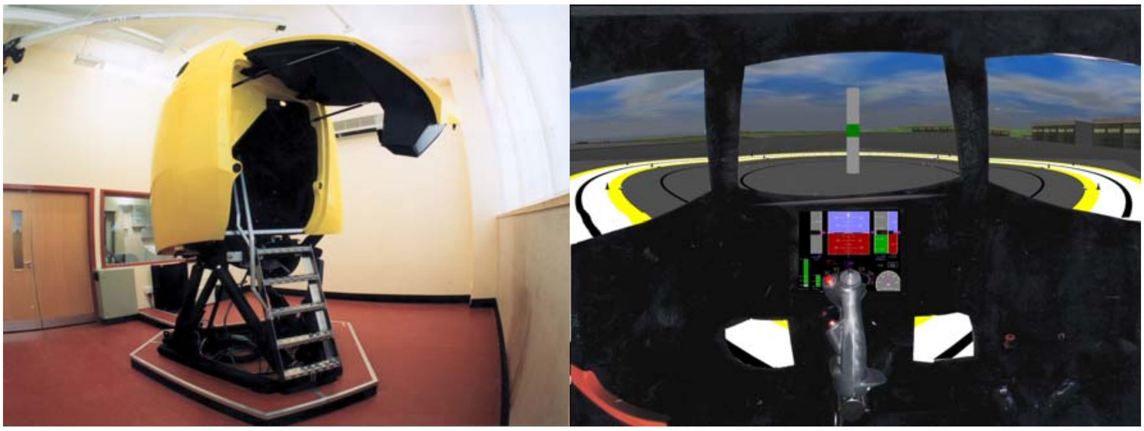

Figure 8 The University of Liverpool ‘HELIFLIGHT’ Flight Simulator & Cockpit View

The HELIFLIGHT facility at UoL (Figure 8) is a PC-based, re-configurable flight simulator developed with five key components that are combined to produce a relatively high-fidelity system [17], 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 relatively wide field of view visual system,

- Computer-generated instrument panel and reconfigurable head up displays.

The FLIGHTLAB software provides a modular approach to constructing flight dynamics models, 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.

2. PREDICTED TILT ROTOR HANDLING QUALITIES

The ADS-33E-PRF hover and low speed dynamic response criteria are split primarily into five categories, small, moderate and large amplitude (pitch, roll and yaw), inter-axis coupling and response to collective. The results presented in this section relate to the unaugmented, or bare-airframe, configuration.

2.1 Small Amplitude Criteria

The small amplitude, short term criteria are based on attitude bandwidth which is the frequency where the response phase margin is 45 degrees, or the maximum frequency at which pilots can double their gain without threatening closed-loop instability. Figure 9 shows the pitch, roll and yaw bandwidth for the three aircraft. Based on the ‘target acquisition and tracking’ boundaries, the three aircraft are predicted to be Level 3 in roll and yaw and Level 2 in pitch. These have been computed by extracting frequency responses from non-linear frequency sweeps. Based on ‘all other MTEs’ requirements, all aircraft are approximately on the Level 2/3 boundary in roll and yaw, while in pitch, the CTR-S and CTR-M are Level 1 and the CTR-L Level 2.

Turning to the low-medium frequency modes, for fully attended operations the damping ratio must be at least 0.35 for Level 1, and meet the limits shown in Figure 10 for divided attention tasks. The chart shows that the CTR-M phugoid mode is Level 2 while the other aircraft are Level 3. All Dutch roll modes are Level 1 for fully attended operations and Level 2 for divided attention. This plot can be used to highlight one of the key issues in the challenge of unifying tilt rotor HQS - the level of augmentation a control system must deliver to bring all configurations into the Level 1 region. For example, the CTR-L augmentation must be much more influential over the phugoid mode than the corresponding controller for the CTR-M model. Furthermore, when designing the controller, the engineer must consider that tailoring the HQs to such an extent may demand the full actuation range of a control surface, resulting in actuator saturation. Therefore, it may not be possible to obtain unified Level 1 handling qualities of three tilt rotors with significantly different baseline characteristics. At the other extreme, as the bare airframe CTR-S and CTR-M configurations are already much closer to the Level 1 region, controllers which deliver unified handling qualities between the three aircraft may in fact not be the optimal solution for delivering excellent handling qualities to the smaller airframes.

In addition to bandwidth being the primary response criteria for short term yaw response, the yaw response to a lateral gust must also be investigated. The requirement states that r_{pk}/V_g (the ratio of peak yaw rate following a step lateral gust after 3 seconds) should not exceed 0.3°/sec for Level 1 or 1°/sec for Level 2. Figure 11 illustrates the yaw rate response of the three aircraft when trimmed in a 10knot lateral gust, to a 25knot step gust. If 3 seconds after the input, the response remains below the boundary line, the yaw gust response is Level 1 and Level 2 if above the boundary line. The CTR-S and CTR-M are Level 2 and CTR-L is Level 1.

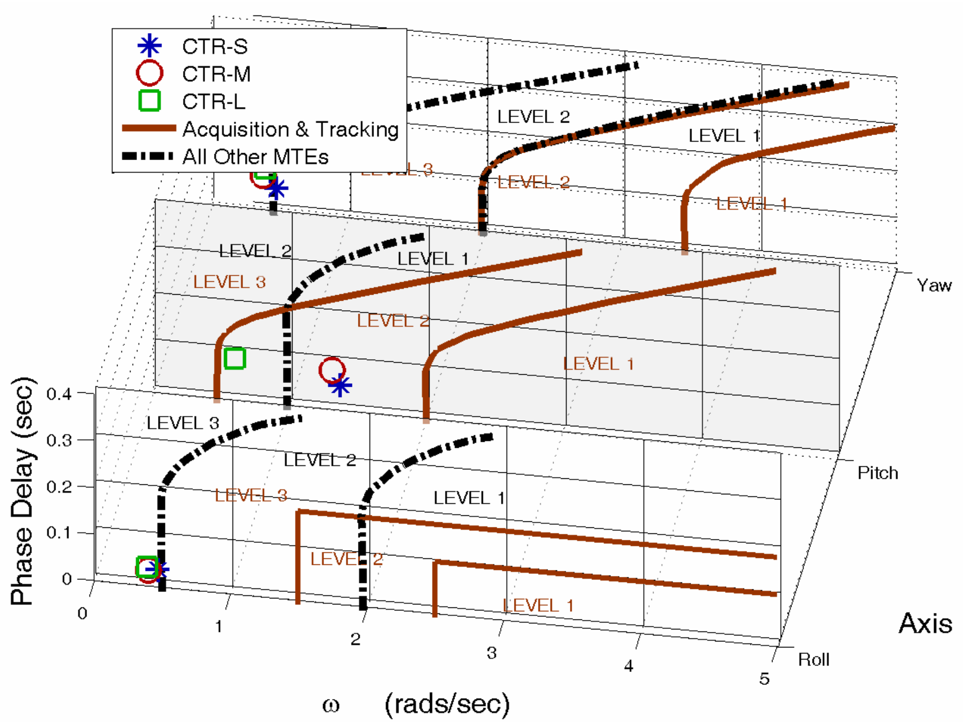

Figure 9 Attitude Bandwidth for the three Tilt Rotor Configurations in Hover

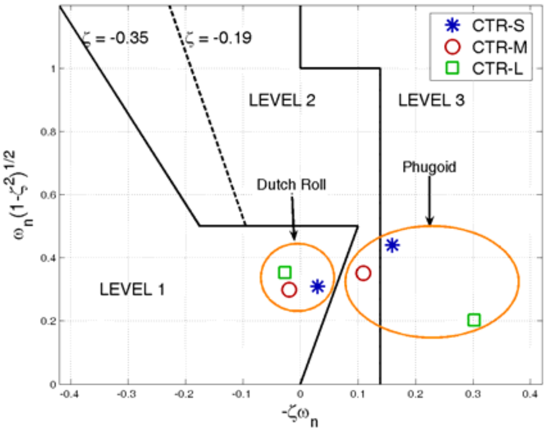

Figure 10 Limits on Pitch (Roll) Oscillations in Hover

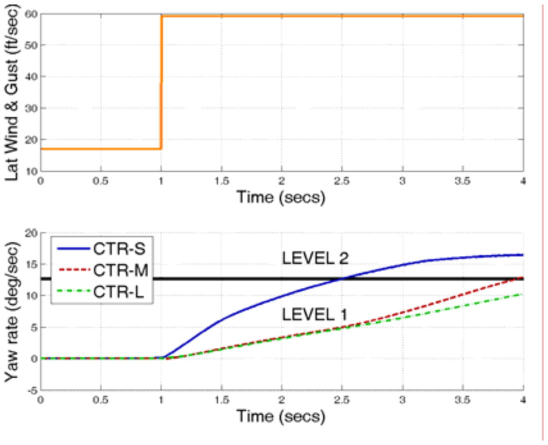

Figure 11 Yaw Response in Hover to a Lateral Gust

2.2 Moderate Amplitude Criteria

Figure 12 illustrates the ADS-33E-PRF roll, pitch and yaw attitude quickness for the three baseline tilt rotor models in hover, showing that, for a tracking task, all are Level 2 in pitch and yaw and Level 3 in roll. However, for ‘all other MTEs’ requirements, all aircraft are Level 1 in pitch, at the Level 1/2 boundary for yaw and Level 2 in roll. Although the quickness of the aircraft is similar in each axis, uniting the quickness in the Level 1 region is likely to be challenging due to the controller having to overcome higher inertias in the larger CTR-L model. The same questions posed during the small amplitude analysis are again raised here - are the required control system designs feasible? Furthermore, is the smaller configuration attaining its maximum capability?

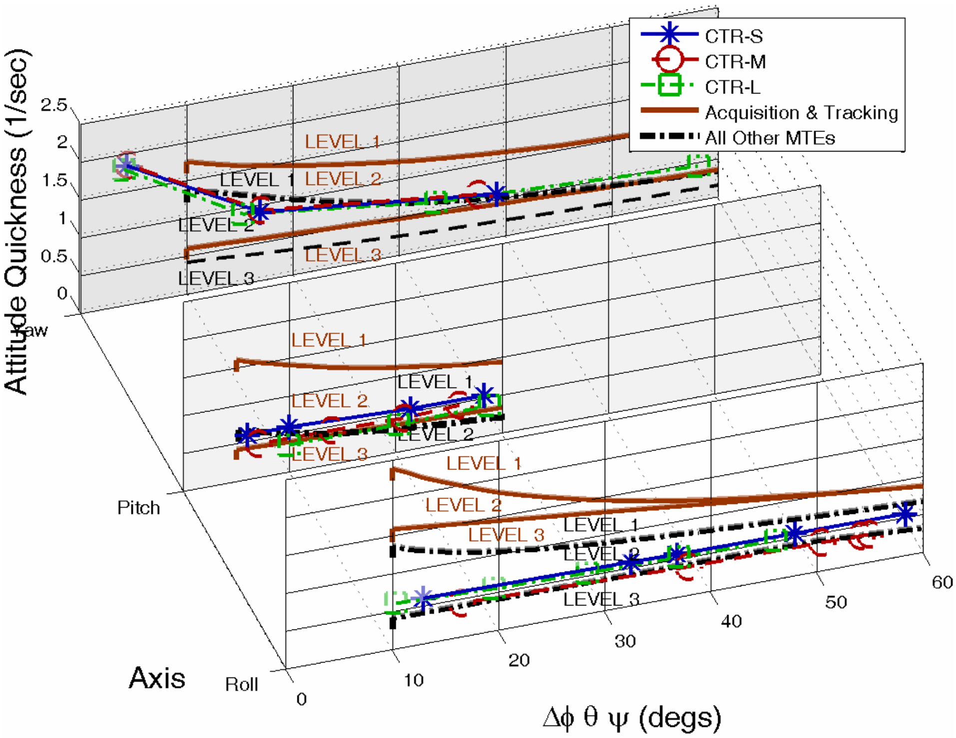

Figure 12 Tilt Rotor Hover Attitude Quickness

2.3 Large Amplitude Criteria

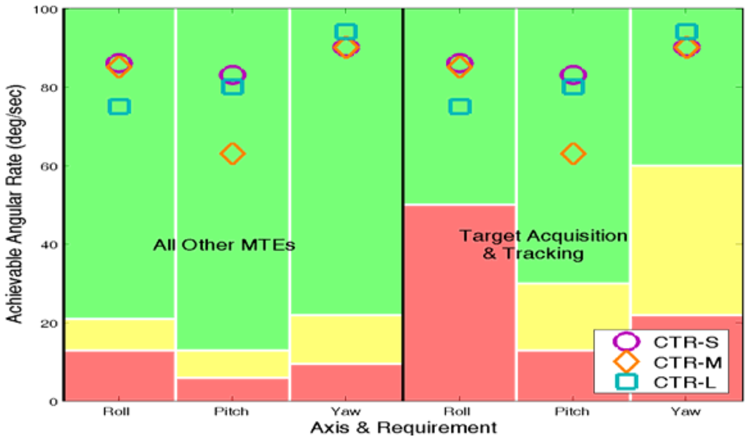

Figure 13 Tilt Rotor Control Power

The ADS-33E-PRF dynamic response criteria measure the maximum angular rates of the aircraft in response to a maximum step control input. Figure 13 illustrates the Level 1, 2 and 3 regions for ‘target acquisition and tracking’ and ‘all other MTEs’ requirements, where the 3 aircraft are all shown to be Level 1, albeit with a long time to steady state due to relatively low damping in all axes.

2.4 Inter-axis Coupling

The ADS-33E-PRF inter-axis coupling requirements relate to yaw response to a collective input and pitch (roll) response due to roll (pitch). These requirements were ‘designed’ for unsymmetrical rotorcraft such as a helicopter. However, due to the CTR designs under evaluation in this paper being symmetrical, no roll results from a trim longitudinal cyclic input. Furthermore, the torque change produced from each rotor in the hover from a collective input cancel out, resulting in zero yaw response.

Therefore of these criteria, only pitch due to roll must be considered. This criteria states that the ratio of pitch to roll angle, 4 seconds after a roll input or gust should not exceed ±0.25 for Level 1 or ±0.6 for Level 2. From Figure 14, all aircraft are well within the Level 1 region.

Although some helicopter couplings are not prevalent in a tilt rotor, there are however new couplings which need to be considered. An example of this is yaw due to roll. Roll is controlled through differential collective in helicopter mode, resulting in an increased torque on one rotor and a decrease on the other, generating a yawing moment as illustrated in Figure 14. Although ADS-33 does not quantify this coupling, ‘the pitch due to roll’ criteria could be applied, in which case all aircraft would still exhibit Level 1 characteristics.

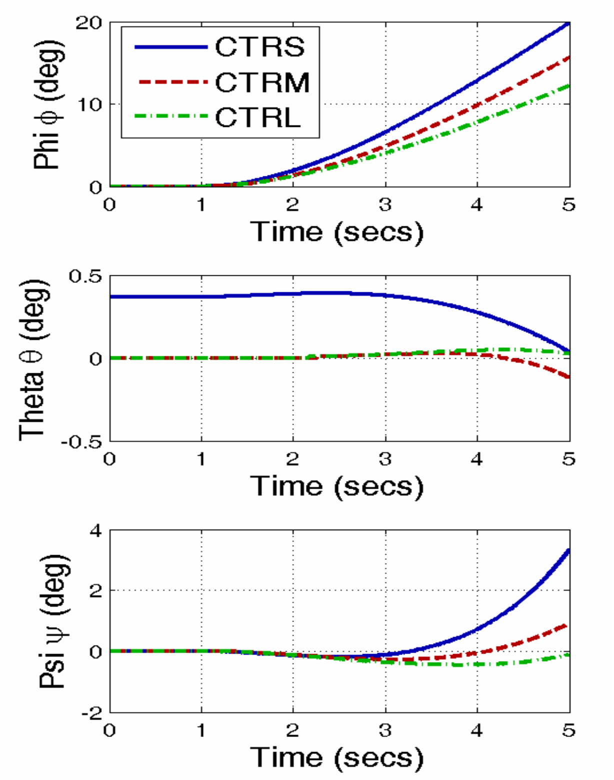

Figure 14 Roll to pitch/yaw Coupling in Hover

2.5 Response to Collective Controller

The heave axis criteria are presented for the tilt rotors in Figure 15. The first illustrates the dynamic torque response in terms of the overshoot ratio and the time to the first peak, which is shown to be Level 1 for each aircraft. The second criterion requires that for Level 1 vertical axis control power, a vertical rate response of at least 160ft/min 1.5 seconds after initiation of a rapid displacement of the collective from trim must be possible. Figure 15 shows that the vertical speed response to a 10% collective input exceeds the Level 1 requirement for all aircraft.

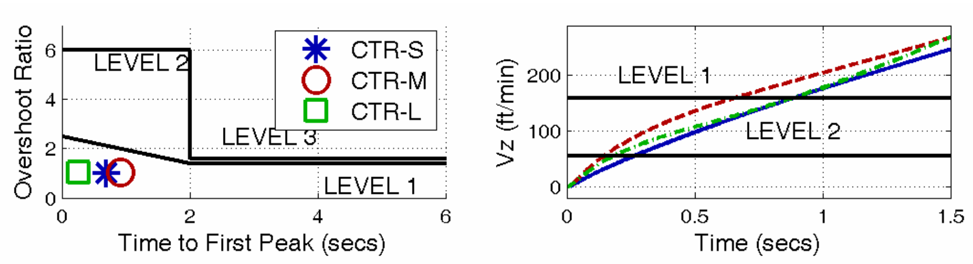

Figure 15 Tilt Rotor Displayed Torque Overshoot & Tilt Rotor Hover Vertical Axis Control Power

2.7 Summary of Predicted HQs

The predicted HQs are summarised in Figure 16. The key points are that for all aircraft sizes, pitch, roll and yaw control power meet Level 1 requirements, while roll and yaw bandwidth prove to be inadequate. For the CTR-S and CTR-L, pitch handling qualities are degraded to Level 3 due to the unstable phugoid mode, while the CTR-M remains in Level 2. This predicted HQ analysis can be used by the control systems engineer to highlight the deficiencies in the system and to establish a basis for the design of control systems that confer Level 1 HQs. However, before this, the results need to be integrated with the assigned HQs from the piloted simulation trial.

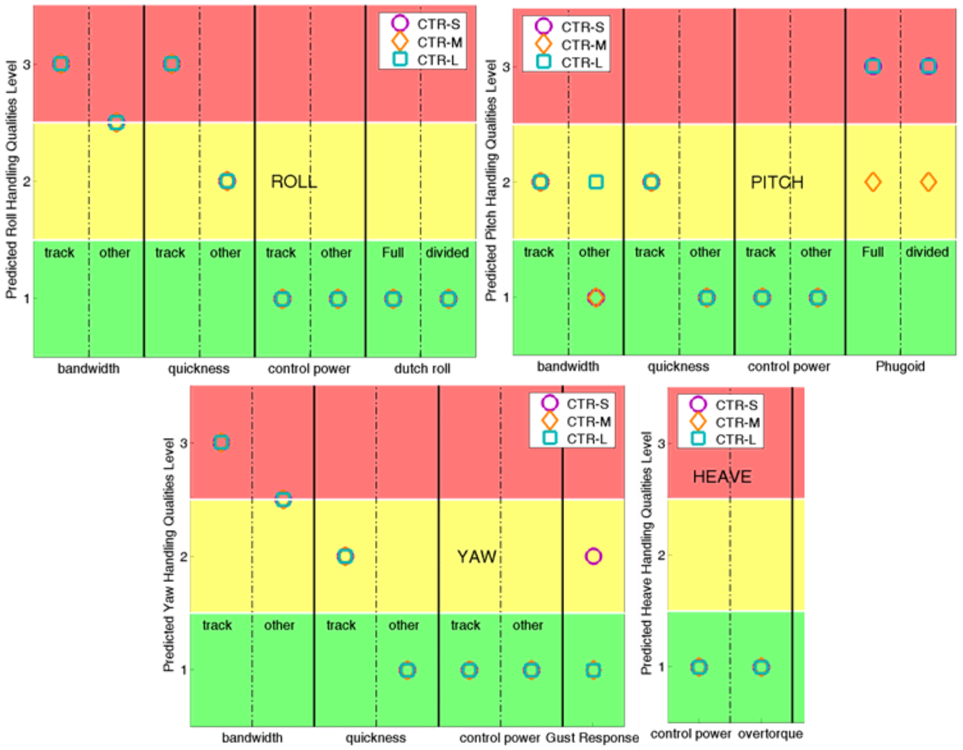

Figure 16 Summary of Predicted HQs

3. ASSIGNED HQs: RESULTS & DISCUSSION

The handling qualities ratings assigned by the two test pilots are shown in Figure 17 for the four low speed MTEs performed with the three aircraft. The solid dark vertical lines represent the HQR spread for each MTE while the dashed line connecting the hover-turn/bob-up, disturbance on/off, represents from left to right, the average HQs with increasing task severity, demonstrating that the general trend is for the HQRs to degrade with increasing task severity. This trend is, as expected, mirrored for the disturbance on/off where HQRs degrade with additional pitch and roll disturbances.

The philosophy of ADS-33 emphasises that HQs are mission-oriented, not size oriented. The HQRs recorded in Figure 17 are in agreement with this philosophy, where there is no clear trend between aircraft size and HQR degradation. A final discussion point from Figure 17 is to compare pilot HQRs for any given MTE. Generally there are, at worst, 2 HQR points between the pilot ratings. However, for a few cases, there are up to 5 HQR points difference such as the CTR-L 10 second hover-turn with disturbance. These points are considered further in the following sections, followed by a discussion based upon predicted versus assigned HQs.

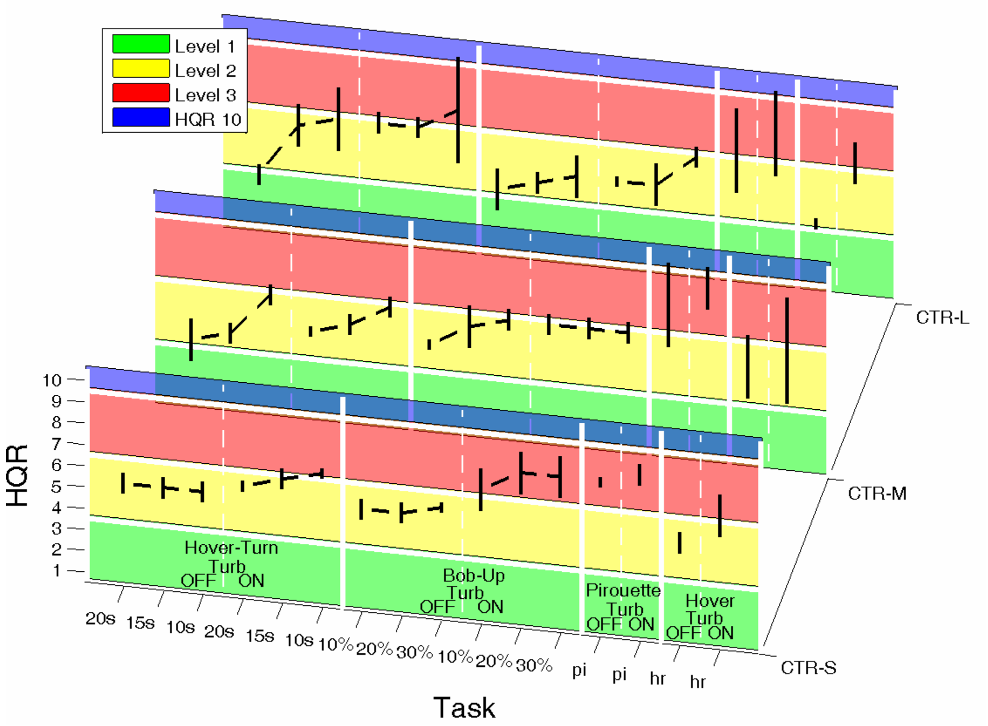

Figure 17 Handling Qualities Ratings (OFF/ON relates to atmospheric disturbances)

3.1 Comparison of Pilot Ratings

Figure 18 shows the recorded time histories for both pilots flying the aggressive 10 second turn in the CTR-L with disturbance on, showing that both met the adequate height performance requirements listed in Table 2. However, from the longitudinal and lateral position figure, both pilots exceeded adequate boundaries (the pilots were not provided with enough visual information to detect small plan position changes through the chin windows). Pilot A returned an HQR 10 and pilot B an HQR 5. From Figure 18, it can be seen that pilot A initiated a faster turn rate, but when attempting to capture the new heading, could not arrest the yaw rate. The figure shows that a full pedal input was applied for over 3 seconds in an attempt to stop the yaw, meanwhile heading overshot by approximately 30°. The pilot commented that while the full pedal input was applied, he felt he had no control in the yaw axis; the yaw rate could not be stopped, thus he returned an HQR 10; although control was not lost per se, the pilot considered that he had run out of control while still commanding the manoeuvre and in his view this warranted the Level 4 rating. Pilot B, with a lower turn rate did not experience loss of yaw control; however, on examination of the pedal input chart, almost a full input was needed to halt the yaw rate. From the assigned HQ analysis, the CTR-L has a high Level 1 control power (Figure 13), but the long time to steady state associated with reaching it results in a low yaw quickness, hence the pilots applying large prolonged inputs to stop the yaw. Even though at first glance the HQRs are in conflict, it can be argued that the difference in the HQRs can be explained by first focusing on the time taken to complete the 180^{o} turn. The pilots were requested to complete the turn in 10 seconds; however, pilot A took less time than Pilot B, therefore generating a larger yaw rate. Although the tilt rotors have Level 1 control power and could negate the yaw rate, when the full pedal input was applied to decelerate, it took several seconds to reach the commanded yaw rate due to the long time to steady state. It is recommended that this task be performed with more test pilots to explore this anomaly further.

In addition, as a result of the injected pitch and roll disturbances, the pilots were continually applying longitudinal and lateral stick inputs during the turn to maintain, as accurately as possible, plan position. The extra workload in this case was off-axis and any additional yaw workload was due to yaw from roll coupling and did not significantly impact upon the HQRs as the disturbances were small (from Figure 11, yaw response to a gust is Level 1 for CTR-L); however this was not so for the bob-up task.

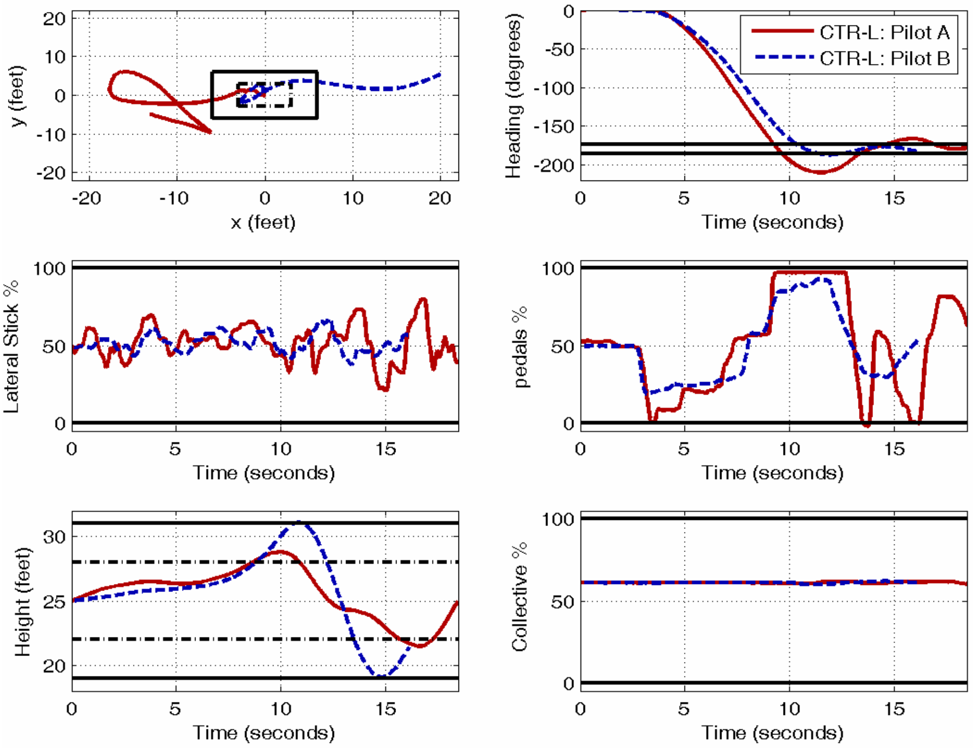

Figure 18 Aggressive CTR-L Hover-Turn: Turbulence On

3.2 Effect of Disturbance on the Bob-Up

From Figure 17, the general effect of the disturbance is to degrade the HQs. This is perhaps most evident for the CTR-S bob-up task where all but one of the 6 recorded HQRs degrade from Level 2 into Level 3. Although the bob-up is nominally a single axis task in the tilt rotor, pilot A found that in addition to vertical axis workload in the stabilisation phase of the task, considerable control activity was required to suppress the additional roll and pitch disturbances, degrading the HQR from 6 to 8. This is demonstrated in Figure 19 for roll where the pilot applied large (compared to the no disturbance case) oscillatory lateral stick inputs to nullify the bank angles. Furthermore, as a consequence of the varying roll attitude, the aircraft drifted in lateral position and the pilot was required to change the aircraft heading in an attempt to maintain the sphere within the inner hover board, requiring 'considerable compensation' from the pilot. It should also be commented that the vehicle drifted aft of the adequate boundaries in both tasks, which was again, as discussed in the hover-turn, caused by a lack of information in longitudinal cues (additional lateral cues were provided by the runway but small longitudinal displacements were difficult to perceive from the ground texture).

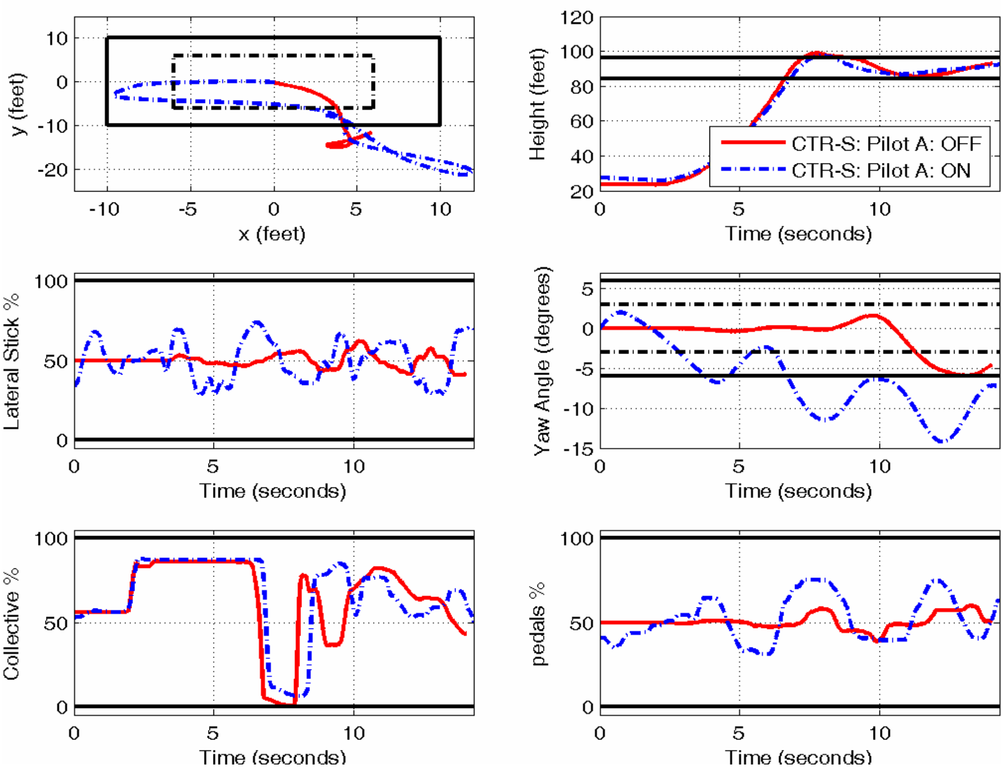

Figure 19 CTR-S Bob-Up: Disturbance On & Off

3.3 Comparison of CTRs for the Pirouette MTE

Of particular interest to this paper is the comparison of HQ results of the three aircraft. It has already been stated that although the predicted HQ analysis showed significant differences between the CTRs, no clear trend exists between the predicted HQs and aircraft size which is in accordance with the ADS-33 philosophy. This conclusion can also be drawn from the HQRs in Figure 17 for any of the MTEs assessed; the pirouette task is perhaps the most appropriate here for an HQR comparison with the 3 aircraft as it assesses performance in all four axes. Results from the pirouette task are discussed for pilot A performing the pirouette with no disturbance for each CTR, where HQRs 8, 10 and 9 were returned for CTR-S, M, L respectively. Figure 20 shows that the pilot not only struggled to maintain adequate plan position throughout the task, irrespective of aircraft size, but required continuous, large, oscillatory longitudinal and lateral stick and pedal inputs in an effort to fly the manoeuvre; part of the problem was the low response quickness highlighted by the predicted HQs. The control traces provide some insight into how hard the pilot was working to maintain plan position, the roll and yaw rates and the pitch nose down attitude required to traverse the course. Although no pitch performance criteria are specified in this task, the pilots commented that the greatest workload from attempting to maintain a pitch nose down attitude (required to balance the centrifugal force generated in the circular motion of the pirouette), was due to ‘excessive’ pitch control power.

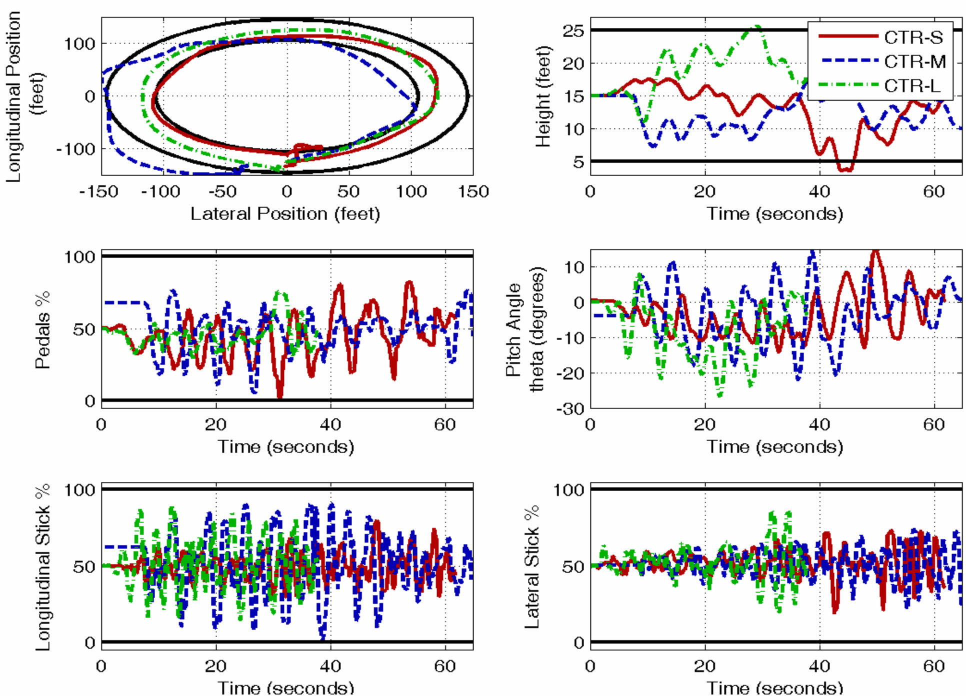

Figure 20 Pilot A: Pirouette Task: Turbulence On

3.4 Discussion of Predicted vs. Assigned HQs

The predicted HQs quantify the expected aircraft behaviour while the assigned HQRs reflect the ease with which a pilot can perform a task to defined performance standards. Predicted HQ Levels on their own are not sufficient to determine the overall HQs, and the assigned HQRs record any deficiencies which may not have been picked up by the criteria or if a combination of Levels further impacts the HQs, degrading them to a poorer Level. Figure 21 is a comparison of the assigned (‘all other MTEs’ and target acquisition & tracking’) and predicted HQs for the CTRs described throughout this paper. The comparison of the results shows good agreement; however some differences are evident.

The hover-turn MTE was predominantly a single axis yaw task where the assigned HQs were mostly Level 2, tending towards the Level 2/3 boundary for high aggression turns. Although the HQ levels are the same for each CTR, it should be noted from Figure 17 that the HQRs differ for each aircraft. These results conform with the ‘all other MTEs’ requirements for yaw bandwidth but the ‘tracking’ requirements for yaw quickness. All aircraft demonstrated the ability to generate the required yaw rate (Level 1 control power as the turn exceeded 60^o), however difficulties in the capture phase proved to be the driving factors for the ratings. When approaching the desired heading, the predicted attitude tracking quickness becomes the revalent criteria (>10 & <60, Level 2 for all aircraft). This philosophy also applies to the ‘disturbance on’ cases where extra workload was generally off-axis. Any additional yaw workload experienced was due to yaw from roll coupling and did not significantly impact upon the HQRs.

The roll axis was predicted to be Level 3 in both quickness and bandwidth for 'target acquisition and tracking', and on the Level 2/3 boundary for 'all other MTEs'. Although the bob-up is primarily a heave-axis task, it was found that with the disturbance on, roll tracking became the influencing factor in the HQRs (Level 3 for CTR-S, Level 2/3 for CTR-M and Level 2/3 for CTR-L). These results also show good agreement with those predicted. However with disturbance off, where the main task was in heave, assigned HQs were Level 2 while predicted HQs were Level 1. The difference between the predicted and assigned Levels can be explained by the pilot not having sufficient longitudinal cueing. The pilots interpreted the longitudinal drift as changes in height due to the resultant vertical motion of the sphere against the hover board, thus increasing workload in collective to maintain the sphere/hover board position.

The pirouette has been shown to be a multi-axis task. However, although the pilots were working hard in roll and yaw, they found that this MTE was dominated by the pitch task. Predicted analysis shows that the pitch control power is well into Level 1 while the bandwidth is, at worst, within the Level 2 for the three aircraft. Predicted HQs show that at low speed the phugoid mode is unstable (Level 3); however, as the pilot is constantly 'closing the loop', the long period of the phugoid mode is not the cause of the high workload for this fine tracking task. The workload is linked to both the control power and attitude quickness, where the control power is very high due to the long time to steady state, making the selection of a pitch attitude imprecise. The results discussed previously relate to the 'disturbance-off' case; however, the disturbance further exacerbated the pitch sensitivity issue, further degrading the HQRs (Figure 16).

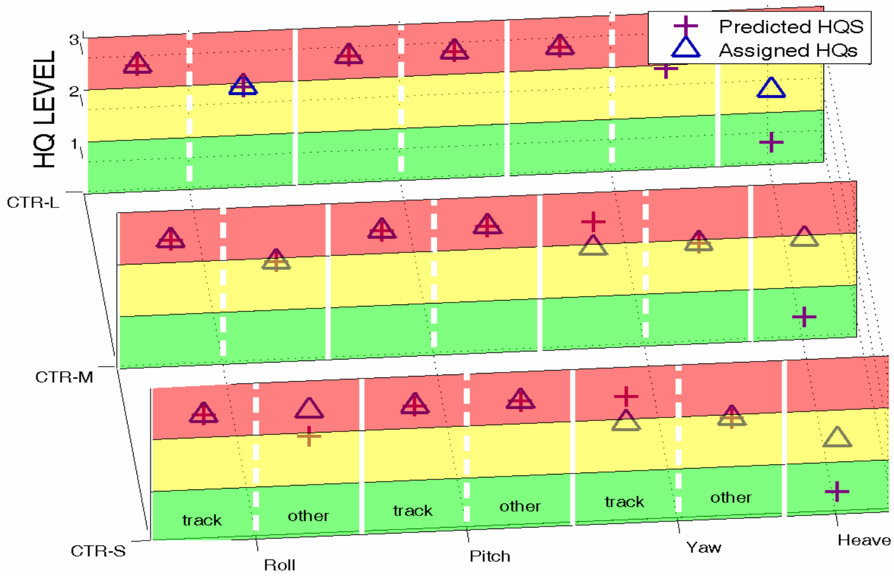

Figure 21 Assigned vs. Predicted HQ Levels

4. CONCLUSIONS

This paper has posed the hypothesis that it is desirable for a family of tilt rotor aircraft (5-15 tonnes) to possess the same handling qualities, allowing pilots to transfer easily between different aircraft types. The predicted handling qualities of three tilt rotors were analysed using the ADS-33E-PRF dynamic response criteria, then compared against assigned HQs from a piloted simulation trial, where two test pilots gave handling qualities ratings, quantifying their ability to perform SAR based MTEs. The HQs were primarily derived against the ‘all other MTEs’ requirements category. It was suspected, and confirmed, however that the precision phases of the MTEs would require the pilot to exercise closed-loop tracking and therefore that the ‘tracking’ boundaries may be applicable. The question then arises as to whether a civil rotorcraft should have to meet the aggressiveness and precision Level 1 ‘target acquisition and tracking’ design standards throughout the OFE, or whether degradation to Level 2 standards is acceptable for a limited time in the mission phases. Reference [2] will return to this question. From the presented analysis, the following conclusions can be drawn:

1. While the CTR-S, CTR-M and CTR-L vary widely in weight and geometry, the predicted analysis showed that the roll and yaw bandwidth, the roll quickness and the pitch phugoid handling qualities all lie within the Level 3 region.
2. From the assigned HQ analysis, the HQs degraded with increasing task aggression and with additional pitch and roll disturbances for the bob-up and hover-turn tasks, as expected.
3. Comparison of predicted versus assigned handling qualities show harmony between the different methods of assessment. The main difference was found to be in the heave axis where Level 1 HQs were predicted but Level 2 was assigned by the pilots. This was explained through poor longitudinal visual cues causing the pilot to lose plan position in the bob-up MTE.

The control engineer must provide controllers not only capable of delivering the performance required to meet a Level 1 specification, but also respecting physical nonlinear aircraft constraints such as actuation rates and actuator ranges. This is especially true in the cases discussed throughout this paper where, the CTR-L configuration has poor bandwidth and quickness characteristics combined with an unstable phugoid mode, meaning the controller must deliver much more augmentation to achieve the same characteristics as the other aircraft. Therefore, the possibility that it may not be physically plausible to unify the handling qualities of three different tilt rotors exists. At the other extreme, where the bare airframe CTR-M configuration is already close to the Level 1 region, a controller which delivers unified handling qualities between the three aircraft is unlikely to be the optimal solution for delivering excellent handling qualities of this vehicle. A second paper presents practical solutions to the control system designs required to unify the HQs for a ‘family’ of tilt rotor aircraft, discussing further the complexities in developing unified handling qualities.

5. ANOWLEDGEMENTS

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