UNIFIED TILT ROTOR HANDLING QUALITIES; FEASIBLE OR IMPRACTICABLE? PART II: CONTROL CONCEPTS

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Abstract: Endowing all members of a 'family' of civil tilt rotor aircraft with identical level 1 handling qualities would allow pilots to convert between aircraft with minimal training. A complementary paper presented results of a study of the 'bare airframe' handling qualities of a 'family' of three tilt rotor aircraft, highlighting the challenges to be addressed in unifying handling qualities. This paper presents a solution to the difficulties, with a model following controller that delivers 'unified', Level 1 performance across the hover and low speed envelope. The controller is assessed via predicted HQs against the ADS-33E-PRF dynamic response criteria, and via assigned HQs in a piloted flight simulation environment. 'Unification' has been achieved across the family of aircraft for both predicted and assigned HQs, and it has been shown that it is possible for pilots to 'convert' from one member of the family to another with minimal 'retraining' time. However, very large control surface displacements are required for the largest aircraft to achieve the specified HQs within the Level 1 region, and it may be difficult to implement this design in practice.

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 modern HQ standards make it clear that HQs are mission-oriented, not size oriented. With vertical flight capability, future Civil Tilt Rotor (CTR) aircraft will be designed to meet customer demands such as short haul 'point to hub' operations or search and rescue roles, operating within busy airports and to/from confined areas. It is hypothesised that efficiencies in tilt-rotor operations, with different payload requirements, could be minimised if commonality between the handling qualities (HQs) of different aircraft sizes existed. As such, it is considered desirable for all members of a 'family' of tilt rotor aircraft to possess identical Level 1 handling qualities, allowing pilots to convert between aircraft with minimal training.

This, the second of two papers, and companion to [1], describes possible control strategies that can be used to bring about unification of the HQs of 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 analysis representing each of the size categories and shown in Figure 1 are based upon the Bell/NASA/Army XV-15 [2] and the Eurocopter Eurotilt and EuroFAR concepts [3, 4]

Figure 1: XV-15 (left), Eurotilt (centre) and EuroFAR (right)

In addition to bringing about the unification of the HQs of the aircraft, it is essential that all handling qualities requirements, such as those specified in ADS-33E-PRF [5], hereafter referred to as ADS-33, are met. As reported in [1], with no control augmentation, the tilt rotor aircraft have significant handling deficiencies in and around the hover, including unstable modes, low bandwidth and low attitude quickness. The results of [1] are summarised in section 2 below.

One control technique that has been successfully used in the past to improve the handling qualities of an aircraft goes under the general heading of 'model following' [6, 7]. The primary response of the aircraft in each axis is specified in terms of a low-order transfer function that captures the desired handling qualities, in this case as specified in ADS-33. Traditional control techniques can then be used to drive the response of the aircraft towards the response of the ideal transfer function model. This technique is attractive in the present context as the same equivalent system model can be used for all three aircraft, leading to, at least in principle, unified, handling qualities. Vehicle dynamic limitations always impose constraints on achievable performance in model following systems of course, and a corollary is that the unification process will be most constrained by the least agile aircraft configuration.

The control system development has focussed on low speed, helicopter mode operations, where, as reported in [1], the bare airframe, unaugmented, dynamics of the three aircraft are significantly different, although it is envisaged that the methodology presented here can be extended to the full flight envelope, including conversion and aeroplane modes, in the future.

The FLIGHTLAB modelling software [8] has been used to develop and analyse the tilt rotor models. A description of the procedure used to construct the simulation models of the XV-15 and Eurotilt is provided in [9]. The modelling of EuroFAR has been accomplished by scaling the Eurotilt simulation, with the principal dimensions increased and with four-bladed rotors replacing the three-bladed rotors of Eurotilt. UoL's HELIFLIGHT motion flight simulator [10] has been used to conduct the piloted simulations of the aircraft.

2. THE CHALLENGE

With three aircraft which have significantly different configurations (see Table 1), even if HQs were unified at, say, Level 2, very different levels of augmentation would be required to maintain unification and improve HQs to Level 1. As noted, the HQs of the three unaugmented tilt rotor aircraft vary greatly, and so a further level of complexity is introduced to the task. Reference [1] explores the issues and difficulties that have to be addressed in the design of a controller that confers unified, Level 1 HQs on the aircraft. A brief summary is presented here.

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)

One of the first and most significant HQ issues with these aircraft is very low attitude response bandwidth in all axes, especially roll and yaw, likely to result in difficulties with precise control of the aircraft during tracking tasks. Coupled with this is the poor attitude quickness in each axis and instability of the Phugoid mode – especially so with CTR-L.

Another cause of difficulties in flying the unaugmented aircraft is the lack of a pure rate response type in each axis, especially in yaw, which has an almost acceleration response type, making the selection and holding of a desired yaw rate very difficult. These difficulties are exacerbated by long times to reach a steady state, resulting in poor predictability and precision. Figure 2 shows the pitch and roll responses to pulse inputs and yaw response to a doublet input of CTR-L in hover. Additionally, cross coupling between axes can be significant, particularly collective to pitch and yaw due to roll, although 'traditional' rotary wing couplings such as yaw due to collective and roll due to pitch are not an issue, as the torque changes on each rotor cancel with a collective input and as the aircraft under investigation are symmetrical about the longitudinal axis.

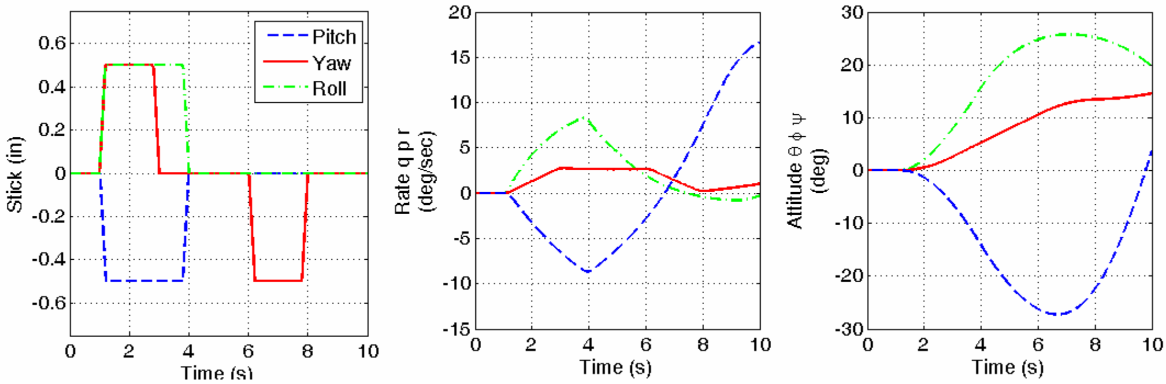


Figure 2: CTR-L Pitch, Roll and Yaw responses in hover

In piloted simulation, pilots found that, even for relatively simple, single axis tasks such as a hover turn, high workload was required to achieve even an adequate level of performance, particularly in suppressing off-axis oscillations resulting from the poor stability of the aircraft.

Unaugmented, the three tilt rotor aircraft exhibit fairly similar lateral HQs, while HQs in the pitch axis vary from aircraft to aircraft. A summary of the predicted and assigned HQs for the unaugmented aircraft is shown in Figure 3.

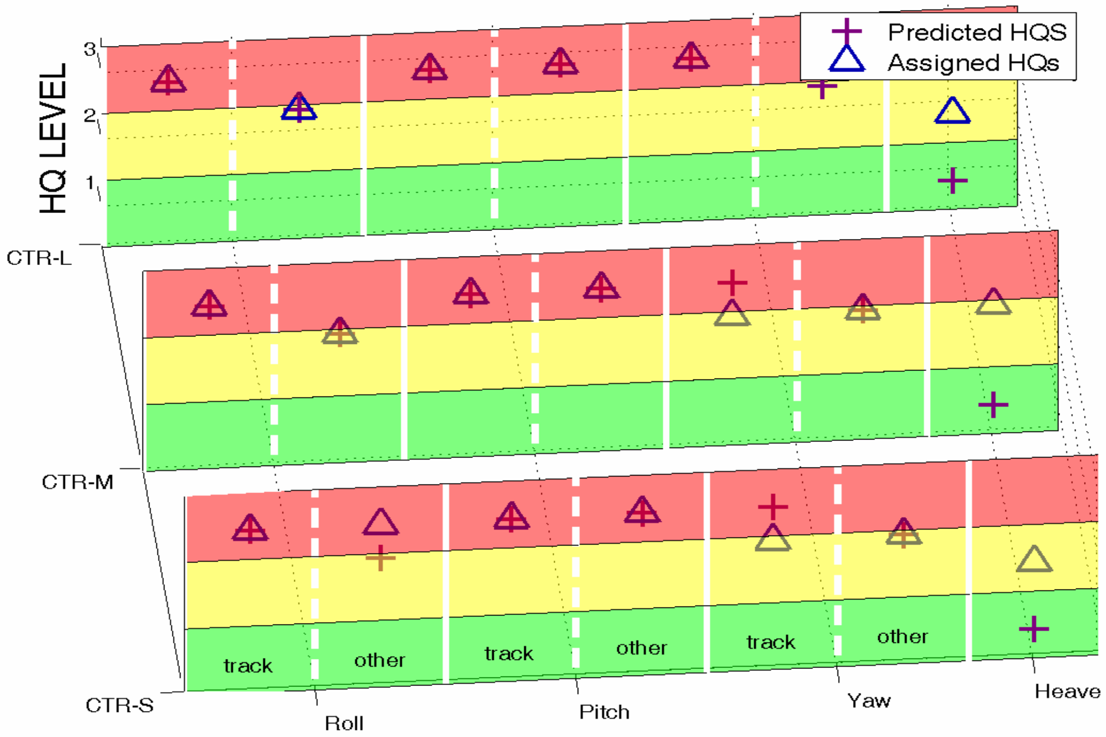


Figure 3: Predicted and Assigned HQs for unaugmented aircraft

3. CONTROL DESIGN

The primary method of control for the pitch, roll and yaw axes is a model following system delivering rate command. While this would imply operation in UCE=1 only, rate command was selected as the lowest allowable level of stabilisation in order to 'prove the concept' of the model following controller. Supplemental techniques used to improve handling qualities include feedback of climb rate in the heave axis and the implementation of position and height hold systems.

3.1 Model following control

Model following control allows the response of an aircraft to control inputs to be specified, bringing two notional benefits. Firstly, a desired response that confers Level 1 HQs can be specified, and secondly, if all three aircraft follow the same model, each should behave in a similar way, thus bringing about unification of the handling qualities.

The response was specified in terms of a second order transfer function model of the form (for the pitch axis) given in equation (1).

$$\frac{q}{X_B} = \frac{K_{X_B}}{(s/\omega_n)^2 + 2\zeta(s/\omega_n) + 1} \tag{1}$$

Where q is the pitch rate; X_B is the longitudinal stick displacement; K_{XB} is the gearing; ω_n is the natural frequency and ζ is the relative damping.

The natural frequency and damping parameters can be varied to adjust the speed of the response and the degree of overshoot, and can thus be related to the attitude quickness, bandwidth and stability of the system, making the link with prescribed handling qualities.

An identical procedure can be used to select the transfer function models for the roll and yaw axes. As the models for pitch, roll and yaw act independently, there is no explicit provision to reduce cross couplings. However, given the controller is of a command structure, if the pilot does not move his controls, the system will attempt to maintain the currently commanded rate, and so cross couplings will be suppressed.

3.2 Model following implementation

In order to facilitate initial controller design, the model following controller was firstly implemented on linearised models of the three aircraft, with the architecture for a single axis shown in Figure 4.

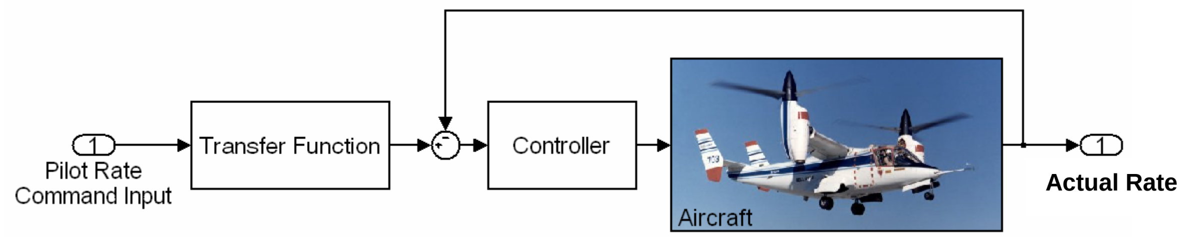


Figure 4: Model Following Controller Structure

The controller block includes the controller itself (of the classical proportional and integral (PI) type), as well as representations of the control system actuator rate and displacement limits. For each aircraft, gains were manually selected for each control axis that minimise the error between the ideal transfer function output and the behaviour of the aircraft. The pilot rate command is derived from the cockpit control movements through gearings that represent the desired control power. A 20% margin over the ADS-33 aggressive agility requirements has been taken for pitch and roll. However, as will be discussed later in the paper, it was not possible to meet the ADS-33 Level 1 large amplitude requirements in conjunction with the small and moderate amplitude requirements. The specified yaw gearing has thus been reduced sufficiently to enable Level 1 performance in bandwidth and attitude quickness to be achieved. The result of this is a yaw control power of ±45°/s – well within the Level 1 region for moderate agility manoeuvring.

A simple analysis of the controller acting on the linear models was performed, to ensure that the aircraft response matched the commanded input for a wide range of input types. Figure 5 gives an example of the closeness of matching achieved through the PI controller, assessed using a pulse input to the linearised models of the three tilt rotor aircraft.

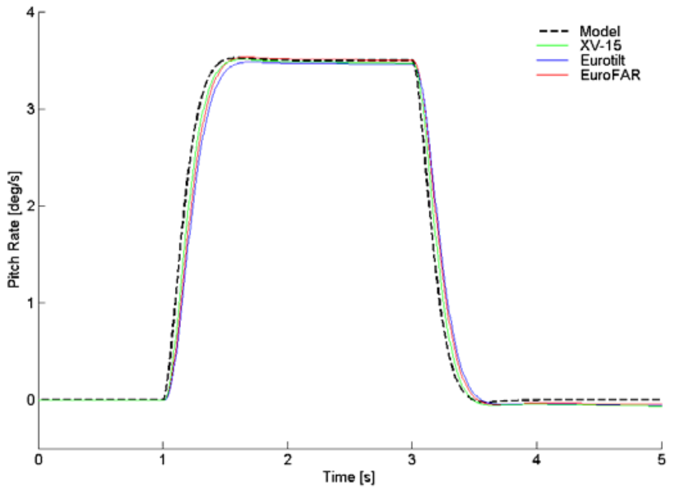


Figure 5: Linear pitch responses to model following controller

With the initial controller design based upon the linear models, it was necessary to check the validity of the design when implemented on the full, non-linear FLIGHTLAB models. Figure 6 shows the responses to a small pitch input of the three aircraft.

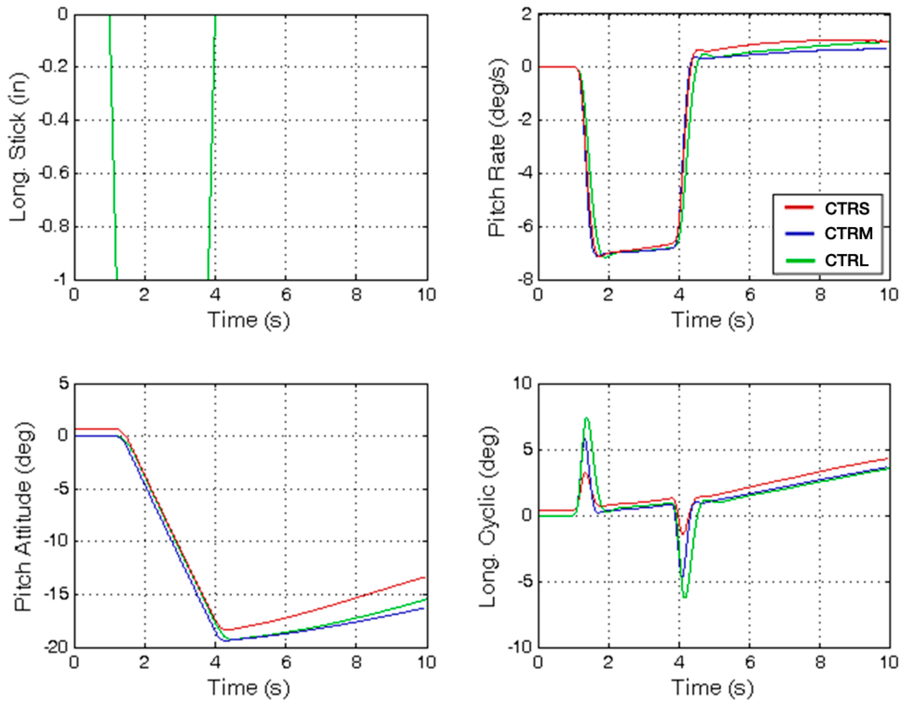


Figure 6: Non-linear pitch responses

It can be seen in Figure 6 that the non-linear pitch response is different to that shown in Figure 5 for the linear models, with a stabilising nose up pitching motion as the aircraft accelerate forwards, away from the hover. Additionally, it can be seen that a large peak of control useage is required to generate the initial angular acceleration. When the commanded pitch rate is reached, the longitudinal cyclic angle reduces to a much lower value which is sufficient to maintain the steady state rate. At the point when the pilot returns the commanded rate to zero, a further (negative) peak in cyclic deflection is required to reduce the angular rate to zero. As would be expected, as the size of the aircraft, and therefore the inertia increases, the cyclic deflection required to generate the specified pitch response becomes correspondingly larger. With a maximum longitudinal cyclic displacement of ±10°, as the commanded pitch rate is increased, the cyclic actuator will saturate, and will remain saturated until the commanded rate is reached, at which point the displacement reduces to the steady state level required to maintain the commanded rate. An example maximum amplitude pulse input for CTR-L is shown in Figure 7. The input required to produce this response would never be found with a real aircraft, as it results in unrealistic pitch attitudes, and is included here purely to illustrate the actuator usage. The effect of this control saturation is that the peak acceleration generated following a step input does not increase linearly as the commanded rate increases, but rather reaches a maximum, constant level as the actuator saturates,

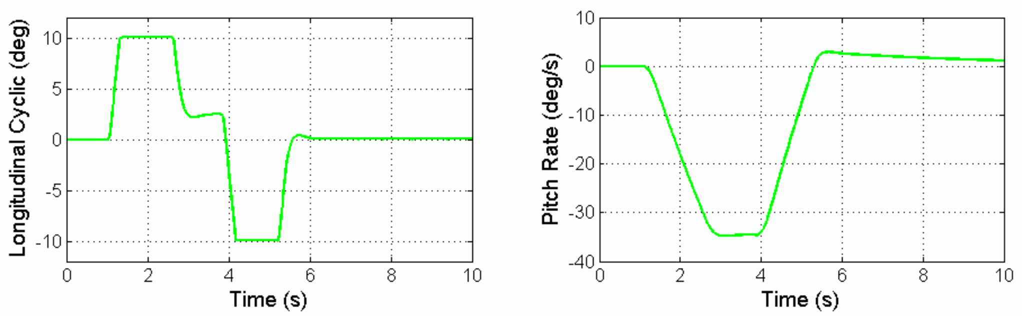


Figure 7: Large amplitude pitch response for CTR-L

These control usage graphs illustrate the level of augmentation required to achieve unified Level 1 HQs with the larger aircraft. Thus, the question must be posed, is it acceptable to demand such large control displacements, or must handling qualities be degraded to Level 2 in order to achieve unified HQs with smaller control displacements?

In the roll and yaw axes, a similar pattern emerges, with a large initial peak to generate the required acceleration, followed by a much lower displacement during the steady state phase. With such disparate control displacement requirements for the same level of performance, it is not surprising that the gains used within the controllers of each aircraft vary considerably. Table 2 shows the proportional and integral gains used in the yaw axis controller of each aircraft.

Table 2: Yaw axis gains

Aircraft	**Proportional Gain, k_p (deg/deg/s)**	**Integral Gain, k_i (deg/deg/s)**
CTR-S	0.6	0.05
CTR-M	0.85	0.1
CTR-L	1.1	0.1

3.3 Supplemental control

In the heave axis, the primary Handling Qualities deficiency in the un-augmented aircraft is the long time to reach a steady state climb rate. This has been addressed through simple feedback of climb rate to the aircrafts' collective systems – this is not a model following system. However, the degree of improvement possible is limited by the torque characteristics of the engines. Even with no augmentation, a torque overshoot exists following a step input to collective. Hence the available margin for improving the heave axis characteristics of the aircraft is relatively small before the ADS-33 'Displayed torque response' requirement degrades from Level 1 to Level 2.

A degree of unification of the heave axis Handling Qualities has been possible through tuning the level of climb rate feedback such that the velocity profile following a collective input is approximately the same for each of the three aircraft.

ADS-33 specifies that the first stage of stability improvement over a basic rate command system for low speed operations is a rate command system with direction, height and position hold functionality. The model following yaw axis system provides excellent holding of a commanded rate, including zero rate, and so it was felt that a heading hold system was unnecessary. The height hold and position hold functions have been implemented, and are pilot selectable.

4. PREDICTED HANDLING QUALITIES

Each aircraft can be assessed through open loop responses to defined control inputs to predict the handling qualities of the aircraft. ADS-33 provides a comprehensive set of dynamic response criteria, covering small, medium and large amplitude rates and attitudes, heave response and couplings into the secondary axes.

4.1 Small amplitude criteria

Sensitivity of aircraft response to small amplitude control inputs is described by bandwidth parameters. Figure 8 shows the pitch and roll attitude bandwidths of the three tilt rotor aircraft in the hover, with and without the model following control system active. These have been computed by extracting frequency responses from non-linear frequency sweeps. The 'bare airframe' results are those presented in [1], and are repeated here to illustrate the level of improvement in Handling Qualities conferred by the model following controller. Where applicable, both the ADS-33 'Target acquisition and tracking' criteria and the 'all other MTEs criteria have been shown.

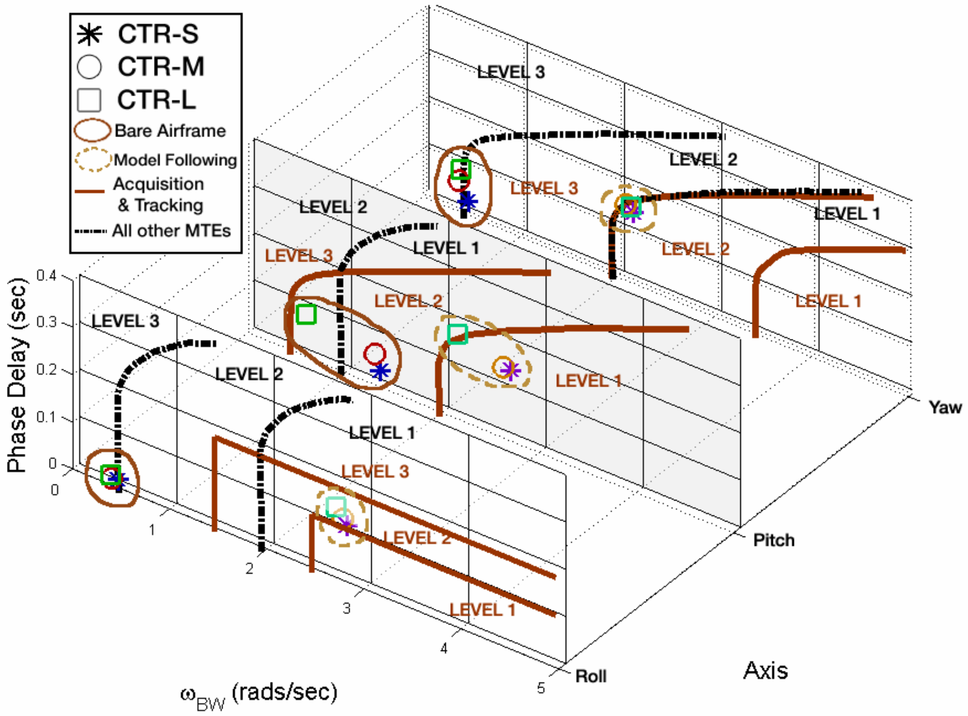


Figure 8: Tilt Rotor Roll, Pitch and Yaw bandwidth in hover

In each case, the bandwidth has been improved markedly. Roll bandwidth has been improved to Level 1 for all three aircraft in the 'all other MTEs' category, with very little variation between the aircraft. The increase in phase delay lowers the 'target acquisition and tracking' performance to Level 2. Pitch bandwidth has been improved further into the Level 1 region, and it can be seen that CTR-M and CTR-S possess very similar bandwidths. CTR-L has a lower bandwidth, and this is indicative of the much increased size and inertia of this aircraft – with the actuator displacement and rate limits available (±10° and ±20°/s respectively), it is not possible to improve CTR-L to the level of the other two aircraft using this method. The yaw bandwidth of all three aircraft is marginally Level 1 (Level 2 for target acquisition and tracking). While this performance is less than that for pitch and roll, it must be remembered that yaw is a very challenging axis in which to deliver Level 1 HQs in tilt rotor aircraft, as the maximum yaw moment that can be generated by the differential longitudinal cyclic controls is small relative to the inertia in this axis. It can be seen that in each axis, the operation of the model following controller increases the phase delay of the response. This is due to the action of the control system model – when a step control input occurs, the error signal acted on by the control system will peak a short time after the input, rather than immediately. The effect of this is to introduce a slight delay into the system, thus increasing the phase delay seen in Figure 8.

The second small amplitude criterion relates to the stability characteristics of oscillations with low-mid frequencies. For tilt rotor aircraft in the hover, these oscillations take the form of the longitudinal Phugoid mode, and the lateral-directional Dutch roll mode. Figure 9 illustrates these modes, and it can be seen that the damping has been improved significantly for the Phugoid mode, with the instability removed, and with the period increased from 17s to 57s for CTR-M for example. This will make the oscillations much less noticeable to the pilot, who will no longer have to manually suppress the Phugoid mode. With the Dutch roll, although the damping has not been increased, the natural frequency has been reduced, so that inputs a pilot makes to suppress these oscillations will occur at a lower frequency, thus lowering workload.

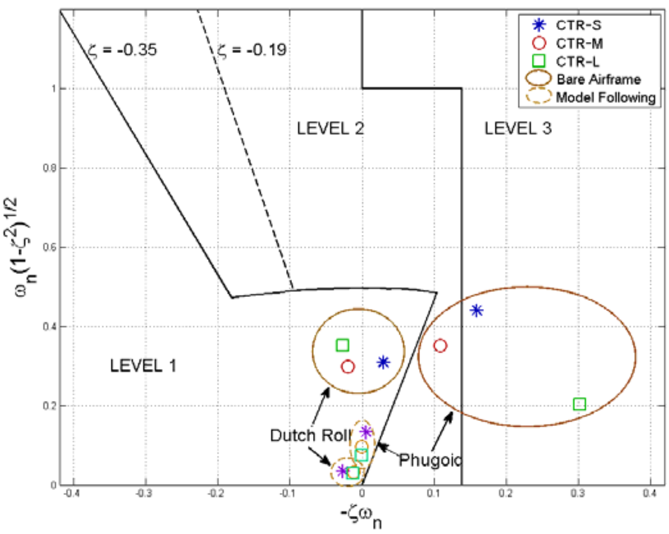


Figure 9: Mid-term responses in hover

4.2 Moderate amplitude criteria

For moderate amplitude attitude changes, the predominant criterion is attitude quickness, illustrated in Figure 10. It can be seen that all three augmented aircraft are Level 1 for pitch, roll and yaw according to the ‘all other MTEs’ category. It should be noted here that roll and yaw quickness are not Level 1 for target acquisition and tracking MTEs.

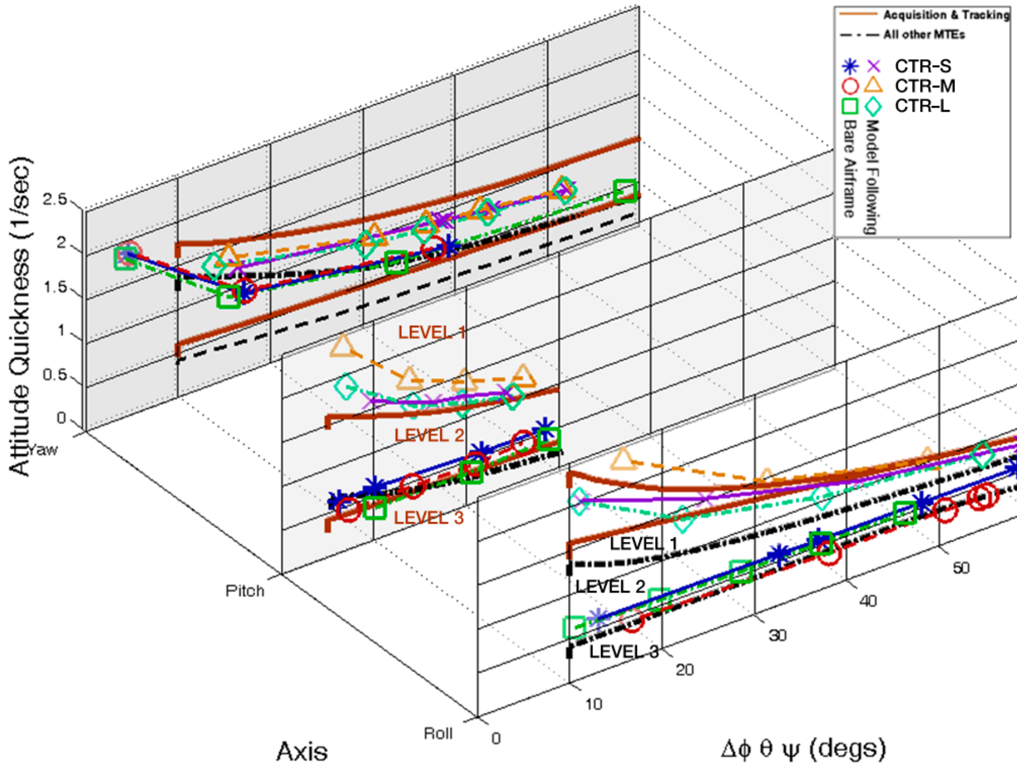


Figure 10: Tilt rotor attitude quickness in hover

It can also be seen that there is some variation between the three aircraft in terms of their maximum achievable quickness. This is because of non-linearities in aircraft response with maximum control inputs, particularly due to saturation of the control actuators with the larger aircraft. If the quickness values are recalculated using 50% of the available control travel (rather than the 100% used in Figure 10), then the performance of the three aircraft matches much more closely, as would be expected with the use of this type of controller. Quickness results using only 50% of the available control travel are shown in Figure 11. This illustrates that the responses of the aircraft in each axis match closely for less-than-maximum inputs.

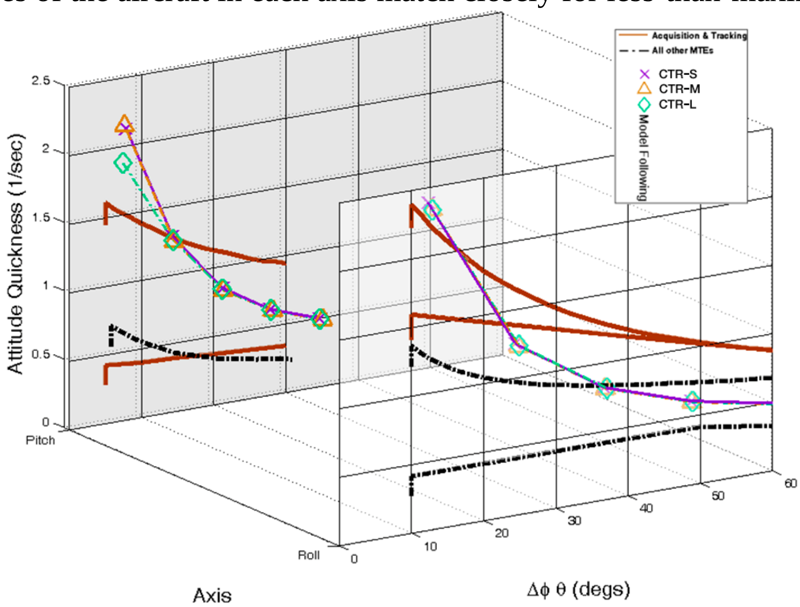


Figure 11: Attitude Quickness using half amplitude control inputs

4.3 Large amplitude criteria

Handling qualities for large amplitude attitude changes are determined by the control power, or maximum achievable rate, in each axis. Figure 12 shows the available control power of each of the aircraft (calculated by applying a maximum control input to each axis and holding until the steady state rate has been reached), compared with the ADS-33 required control power for aggressive manoeuvring.

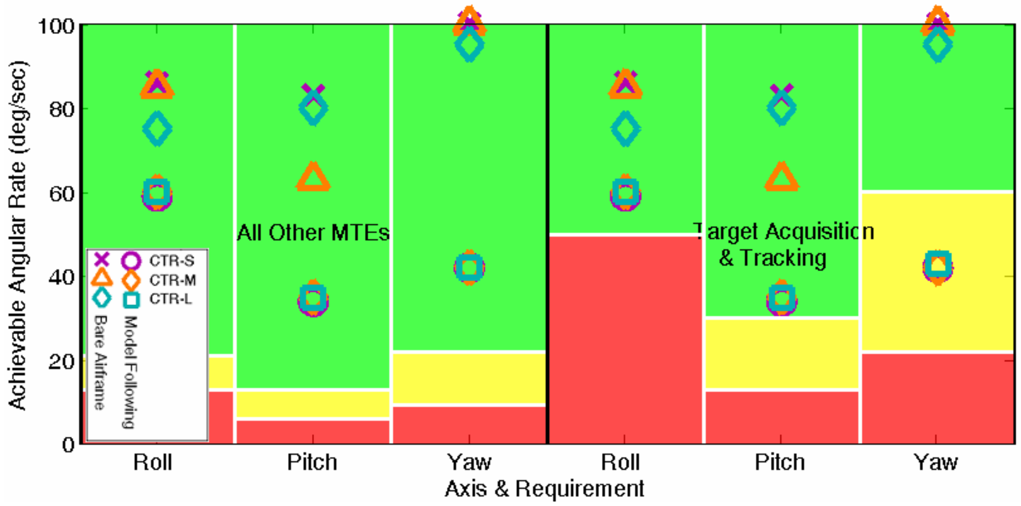


Figure 12: Tilt rotor control power in hover

The Level 1 requirements for pitch and roll are met in all aircraft. It is not however possible to meet the Level 1 requirement for aggressive manoeuvring in the yaw axis without significantly compromising the bandwidth and attitude quickness in this axis. As seen above, these HQs are marginally Level 1 for all other MTEs, and are Level 2 for Target Acquisition and Tracking MTEs. Thus, a lower yaw control power has been selected, which is Level 1 for moderate aggression only. However, this is not unexpected, as the twin rotor configuration of a tilt rotor aircraft does not easily lend itself to rapid and aggressive manoeuvring in the yaw axis.

4.4 Response to collective controller

Heave axis HQ criteria consist of control power, heave response characteristics and torque characteristics. As discussed in [1], the tilt rotor aircraft comfortably meet the ADS-33 heave control power requirements, and this remains unchanged here. The heave response characteristics encapsulate the damping present in the heave axis, and thus the time to reach a steady state. The characteristics of each tilt rotor aircraft are shown in Figure 13, where the response has been normalised to give the same steady state climb rate for each case, thus highlighting the differences in heave damping. As all of the data fall within a small area on the chart, a section has been enlarged to provide a clearer picture.

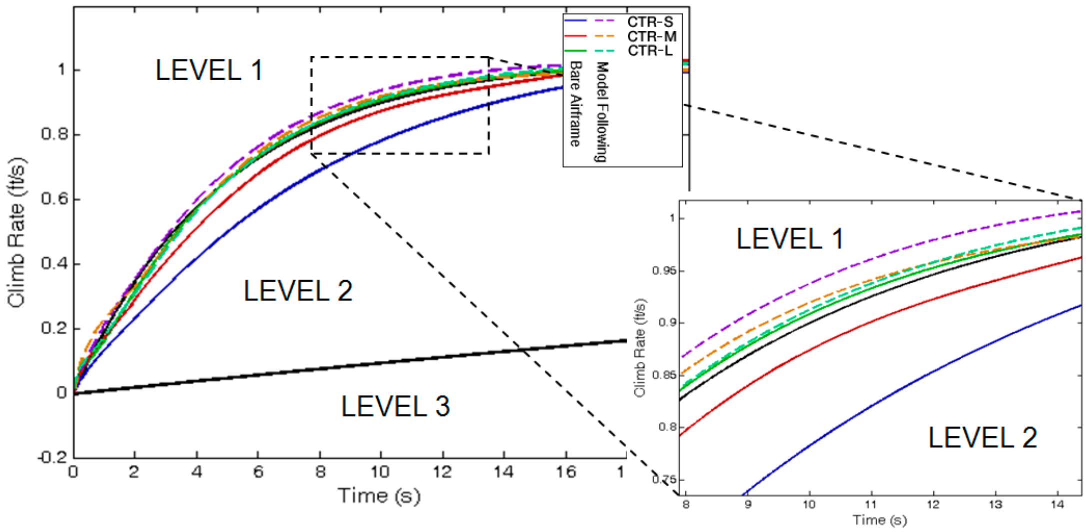


Figure 13: Heave response characteristics in hover

With the un-augmented aircraft, both CTR-M and CTR-S have heave response characteristics that failed to meet the Level 1 criteria (time to steady state is too long, resulting in the heave response falling beneath the black Level 1/2 boundary in Figure 12), while CTR-L was marginally Level 1. In the case of the aircraft with the model following control systems, the Level 1 criteria are met in each case (damping has been improved sufficiently so that the time to reach a steady state vertical rate is less than the maximum specified in ADS-33 for Level 1 performance). As discussed earlier, as the augmentation is increased, so is the torque overshoot. Thus, the amount by which the heave damping characteristics could be improved was limited by the ADS-33 allowable torque overshoot. As seen in Figure 14, the displayed torque is now borderline Level 1/Level 2 in each case.

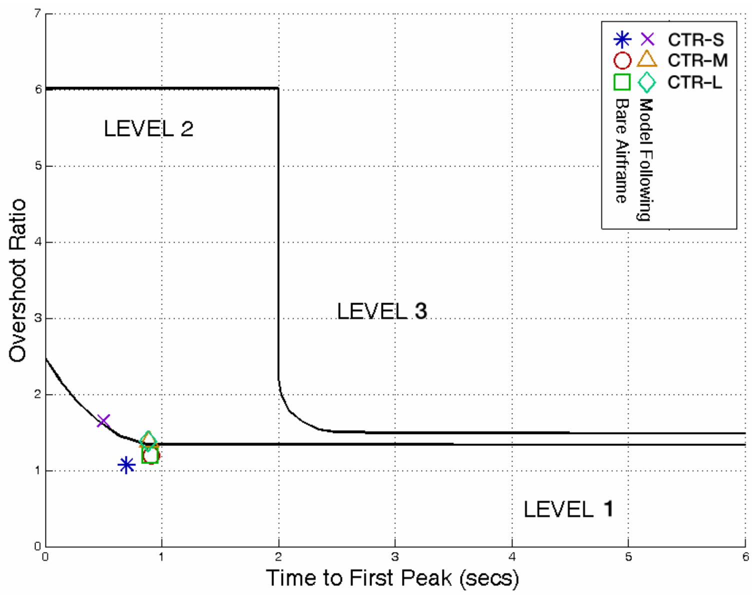
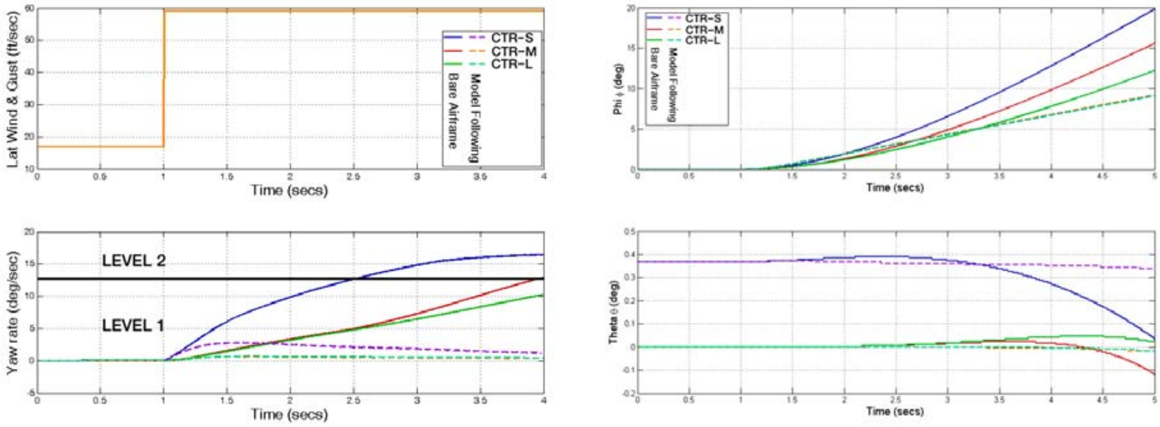


Figure 14: Displayed torque response

4.5 Inter-axis coupling effects

As reported in [1], responses to lateral gusts of the bare airframes lie near the Level 1/Level 2 boundary, with CTR-S Level 2, CTR-L Level 1 and CTR-M on the boundary. With the model following controller active, performance is significantly improved, with yaw rates following the commencement of a gust much reduced. ADS-33 combines the pitch to roll and roll to pitch coupling into one requirement. However, as a tilt rotor aircraft is symmetrical about the longitudinal axis, no pitch to roll coupling exists. The roll to pitch coupling, already Level 1 with the bare airframes, has been further reduced. Figure 15 shows both of these requirements. Other cross couplings have been similarly suppressed.



(a) Yaw due to Lateral Gusts *(b) Pitch due to Roll*

Figure 15: Coupling effects in hover

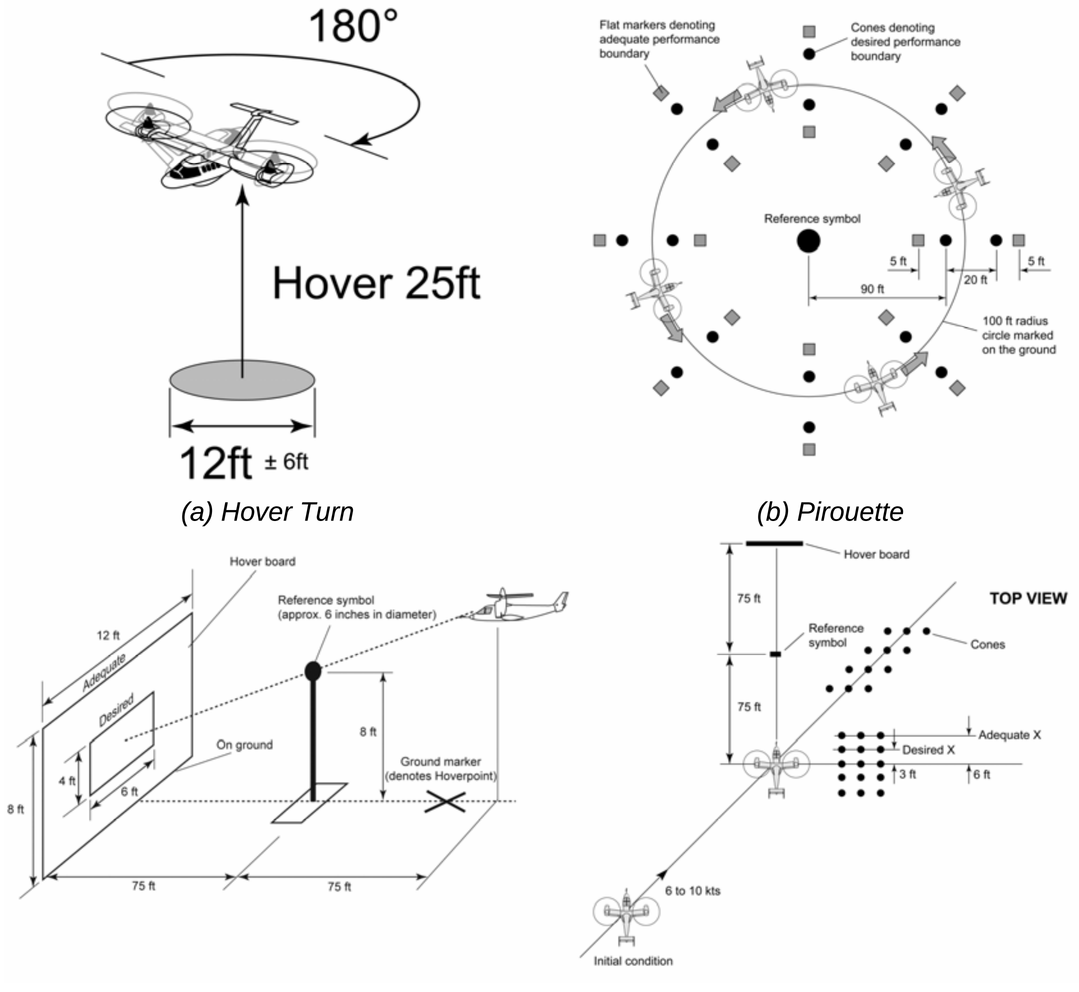
In summary, performance has been unified for all ADS-33 hover and low speed HQs, and, with the exception of yaw bandwidth, which is borderline Level 1/Level 2, all ADS-33 hover criteria are met at Level 1 for operations not involving tracking tasks, i.e. 'all other MTEs'. Several criteria are not met at Level 1 for target acquisition and tracking MTEs, including roll and yaw bandwidth, roll and yaw quickness and yaw control power. These results suggest that performance of the tilt rotor aircraft with the model following controller would allow Level 1 performance for the majority of an SAR mission, which is considered to consist mainly of non target acquisition and tracking MTEs. Although performance is not fully Level 1 for Acquisition and Tracking MTEs, this may be acceptable to pilots so long as they are aware that workload would be elevated (and HQs degraded to no worse than Level 2) for short periods during the mission while high precision is required.

5. PILOTED SIMULATIONS

The augmented tilt rotor aircraft were assessed in piloted simulation, flown in the same manoeuvres used in [1] – the Hover Turn, Pirouette, Vertical manoeuvre and Hover recovery, in accordance with the guidelines in ADS-33. The hover turn manoeuvre involves the aircraft maintaining position over a designated point on the ground while completing a heading change of 180° within a specified time. Three levels of aggression were tested, determined by the time available for the turn – 20s, 15s or 10s. The pirouette manoeuvre is a lateral translation around the boundary of a 100ft radius circle, changing heading such that the aircraft remains pointing at the centre of the circle. The vertical manoeuvre, or bob-up, sees the aircraft maintaining plan position above a point on the ground while climbing 75ft from hover in ground effect to recapture hover out of ground effect. The level of aggression here was determined by the torque change commanded by the pilot in initiating the climb. Three levels were used, 10%, 20% and 30% torque changes from hover. Finally, the hover task involves hover capture from a low speed (6-10kts) at a designated point above the ground. The test courses used for these MTEs are illustrated in Figure 16.

In order to assess the handling qualities of each aircraft during each task, the pilots were asked to rate the manoeuvres using the (Cooper-Harper) Handling Qualities Rating (HQR) scale [11], where a rating of 1 is indicative of the achievement of highly desired performance at low workload, and a rating of 10 indicates major deficiencies which preclude the task from being completed, together with a high risk of loss of control.

As in [1], each manoeuvre was flown initially in still air, and then with a ‘turbulence’ component disturbing the aircraft during the manoeuvre. With the unaugmented aircraft, this ensured that the pilots remained within the control loop for the whole manoeuvre. With the augmented configuration, the control system minimises the disturbances that result from the turbulence, so that, in theory, the pilots can fly ‘through’ the turbulence, without additional workload. The turbulence component thus acts as a disturbance within the control system itself, and performance in these tests can also be taken as an indicator of the robustness of the control system design.



(a) Hover Turn *(b) Pirouette*

(c) Vertical Manoeuvre *(d) Hover recovery*

Figure 16: MTEs for piloted simulation

The aircraft were tested in two configurations: at their standard operating weight, as used for the assessments of [1], and at weights that give the same, reduced, thrust margin for each of the aircraft, in order to accurately assess the unification of heave axis HQs. The thrust margin selected for these tests was 10%, a significant reduction from the thrust margins at the standard operating weights (approximately 25% for CTR-S and CTR-L and 40% for CTR-M). This has the consequence of limiting the maximum aggression that the pilots can apply when flying a manoeuvre, which for the tasks assessed here means the possibility of reduced aggression in the hover capture, and limiting the maximum aggression that can be applied to the vertical manoeuvre.

Considering the primary rationale behind handling qualities unification, it is essential that a pilot familiar with one of the tilt rotor types could operate other family members with no loss of capability during the period of re-familiarisation. To assess this, the pilots were given the opportunity to become very familiar with the HQs of one of the aircraft types during the full assessment of that aircraft. The pilots were then asked to fly the same MTEs with one of the other two aircraft, but were not allowed time to familiarise with the new aircraft before providing an HQR for the task. The rating awarded at this point was compared to the rating awarded during the full assessment of the handling qualities of each aircraft, with any differences being indicative of a lack of familiarisation with the particular HQs of each aircraft.

The results of the piloted simulation of the aircraft operating at their standard weights are presented in Figure 17 below, where the solid black lines indicate the spread between the results from different pilots and the dashed lines represent the average of the assigned HQs as the aggression of the manoeuvre is increased from left to right.

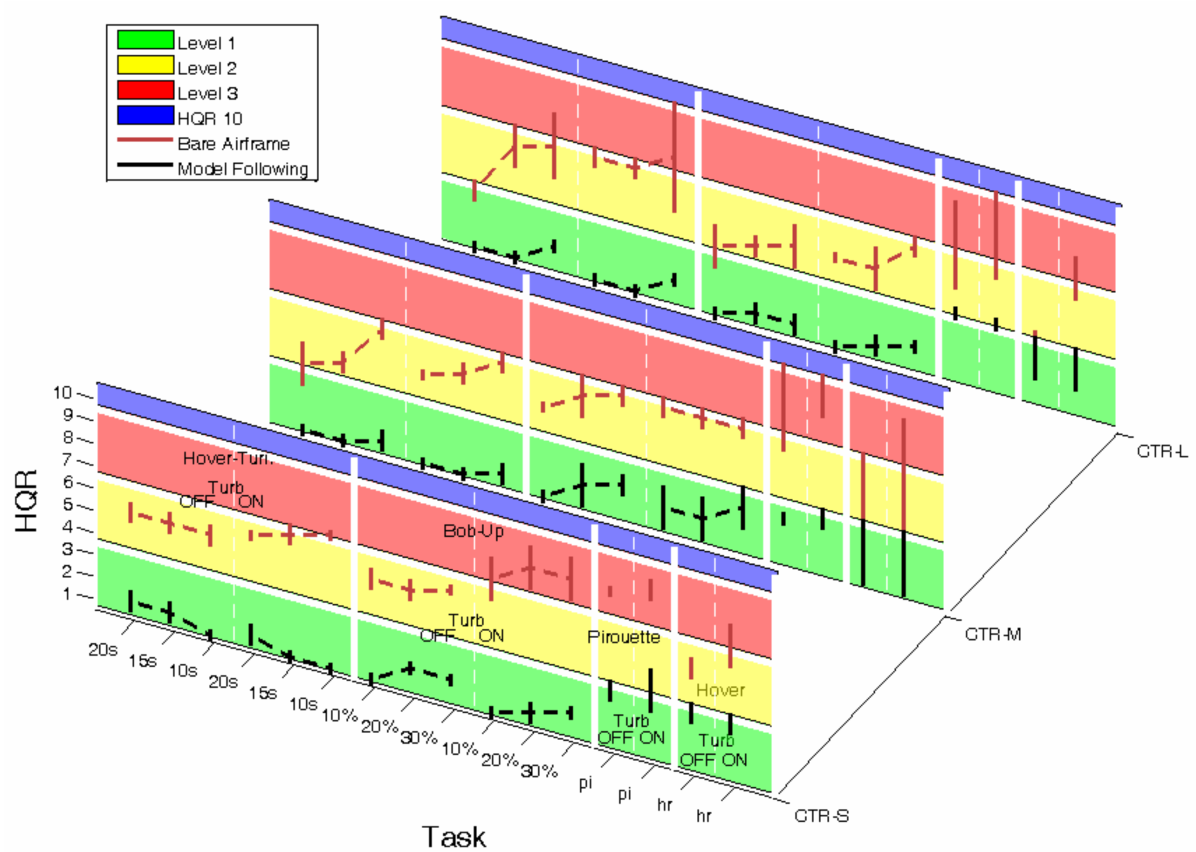


Figure 17: Handling Qualities Ratings for Tilt Rotor aircraft for hover and low speed manoeuvres

It can be seen that the majority of the results lie within the Level 1 region, with the pirouette and hover recovery tasks being the exceptions. A significant reason for this poorer performance was the visual limitations of the simulation environment, where the field of view is restricted. It is noted that the turbulence did not affect the performance during each task, indicating the controller is effectively suppressing the disturbances. Comparing the three aircraft, there is very little difference in the average HQRs for the manoeuvres, and where a variation does exist, it is covered within the spread of results between the different pilots. This result suggests that the HQs offered by each of the aircraft are similar for each manoeuvre. The individual manoeuvres are discussed in more detail in the following sections. As the turbulence makes little difference to the control activity required to complete the manoeuvre and the strategies used by the two pilots are very similar, the comparisons will focus on the differences and similarities between the three aircraft – of critical importance when attempting to provide unified HQs.

5.1 Hover turn

All of the ratings awarded for the hover turn manoeuvre lie well within the Level 1 region, with the majority being HQR 1s, indicating ideal, highly desired performance, with minimal workload. An example of a 10s hover turn manoeuvre is illustrated in Figure 18. The black lines indicate the boundaries of ADS-33 adequate performance.

Although a slightly larger pedal input was used with CTR-M, along with the turn being completed in a slightly shorter time, the overall pattern of pedal input is very similar across the three aircraft, indicating similar handling qualities. A single small corrective input was required to capture the desired final heading, although both pilots commented that this was as much to do with the poor feel characteristics and lack of positive centring of the pedal controls in the HELIFLIGHT simulator, than any deficiency in the controller. It can be seen that position hold functionality is very beneficial for single axis tasks of this type, as it minimises workload not derived from the primary task (in this case, completing the 180° turn in the specified time).

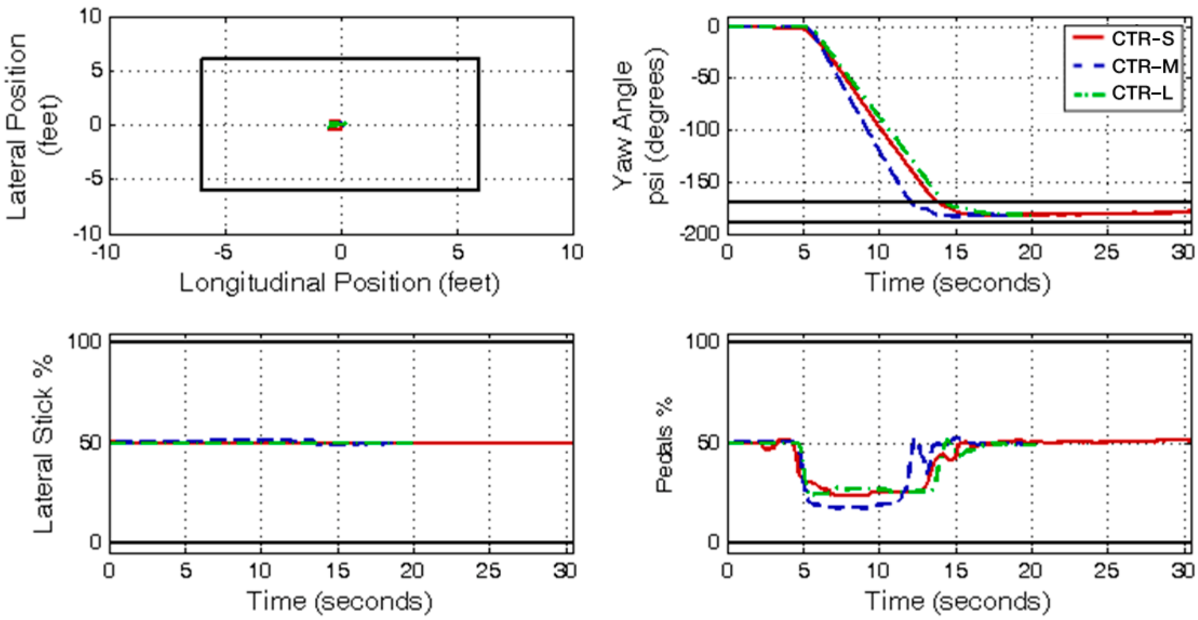


Figure 18: 10s hover turn manoeuvre

With weight increased to give a 10% thrust margin, the performance in this task was largely unaffected, as would be expected for a task that does not require any heave activity. The HQRs awarded did not change from the standard weights.

When the pilots were asked to perform this manoeuvre with no prior time in the aircraft, performance remained essentially constant, with identical HQRs awarded as were given when the pilots had time to familiarise with the aircraft. This suggests that the yaw axis handling qualities of the three aircraft have been unified sufficiently for this task.

5.2 Pirouette

The handling qualities ratings awarded for the pirouette task are worse than those for the hover turn. However, the pirouette is a more demanding manoeuvre, requiring continuous inputs in three axes, and the overall workload will always be greater than in what is essentially a single axis task. Figure 19 gives an illustration of the control activity required during the pirouette task. It can be seen that, although the pilots felt this was a higher workload task, the actual control inputs required to perform the manoeuvre were relatively modest, especially when compared to the very large amplitude and high frequency inputs required for this manoeuvre in [1]. The majority of the workload in all cases was in the pitch axis, which required constant attention to maintain the nose down attitude required to maintain the turn rate. It is believed that the primary reason for this deficiency was a lack of longitudinal cues and the limited downwards field of view in the simulator. Regarding unification of HQs, the magnitude of input required in each axis is essentially the same, although it can be seen that the frequency of pedal input is somewhat higher for CTR-S, although this is likely to be at least partly due to this being the first aircraft in which the pilot flew this manoeuvre, and was therefore possibly still finding the correct control strategy for the manoeuvre. This increased workload did not, however, adversely affect the HQR awarded for the manoeuvre.

At the 10% thrust margin, although this task does involve some activity in the heave axis, performance was largely unchanged, as the altitude hold system overcame any extra workload that might be required to maintain the specified height. The HQRs awarded were the same for both weights tested.

When presented with this task in a new aircraft, on most occasions the HQR degraded by 1 point. However, in one case, the HQR was actually lower (i.e. better) than when the pilot had become familiar with the aircraft. This suggests these results are within the expected statistical variation, and hence it is judged that there would be minimal impact on task performance in converting rapidly from one type to another.

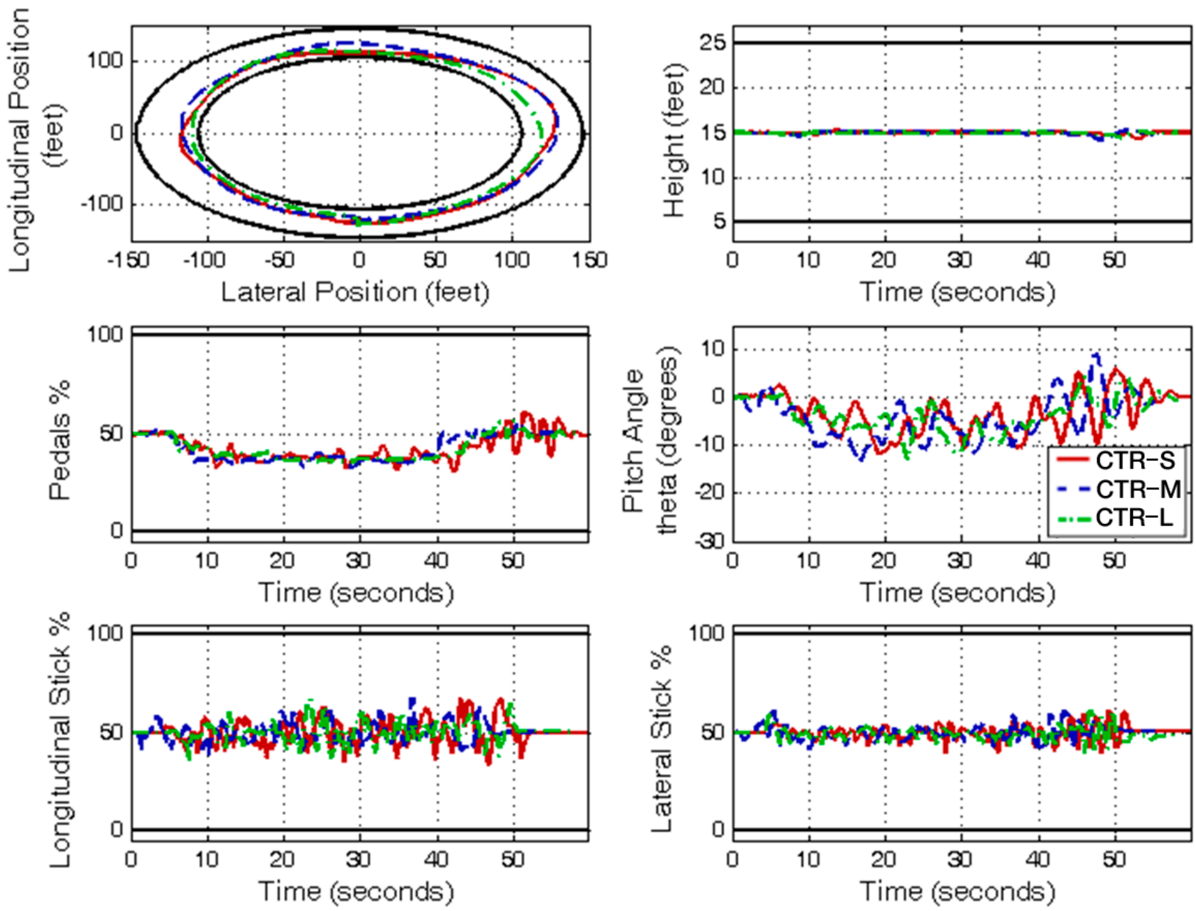


Figure 19: Pirouette manoeuvres

5.3 Vertical manoeuvre

As with the hover turns, the bob up tasks were reduced to activity in a single control axis through the function of the plan position hold system, and hence performance was very good, despite the relatively modest improvement in heave axis handling qualities described in section 4.4. Figure 20 shows three bob up manoeuvres performed in each of the aircraft (10% torque increase at 10% thrust margin). The control inputs used by the pilot were very similar for each aircraft, although an extra collective input was required with CTR-L as the pilot started the deceleration phase early, resulting in the climb being arrested at too low a height.

It was expected that in this task, more than any of the others, the reduction in thrust margin would be most noticeable by pilots. It was not possible to perform a bob up with a 20% or 30% initial torque change, as this would have resulted in exceeding 100% engine torque. However, for the remaining, lowest, level of aggression (10% torque change), the HQRs remained similar to those at the standard weights, despite the significant reduction in excess thrust available.

When asked to fly the bob-up with no familiarisation time in any of the aircraft, there was again very little change in task performance from that described above, suggesting it is straightforward for pilots to convert from one type to another and perform this type of manoeuvre.

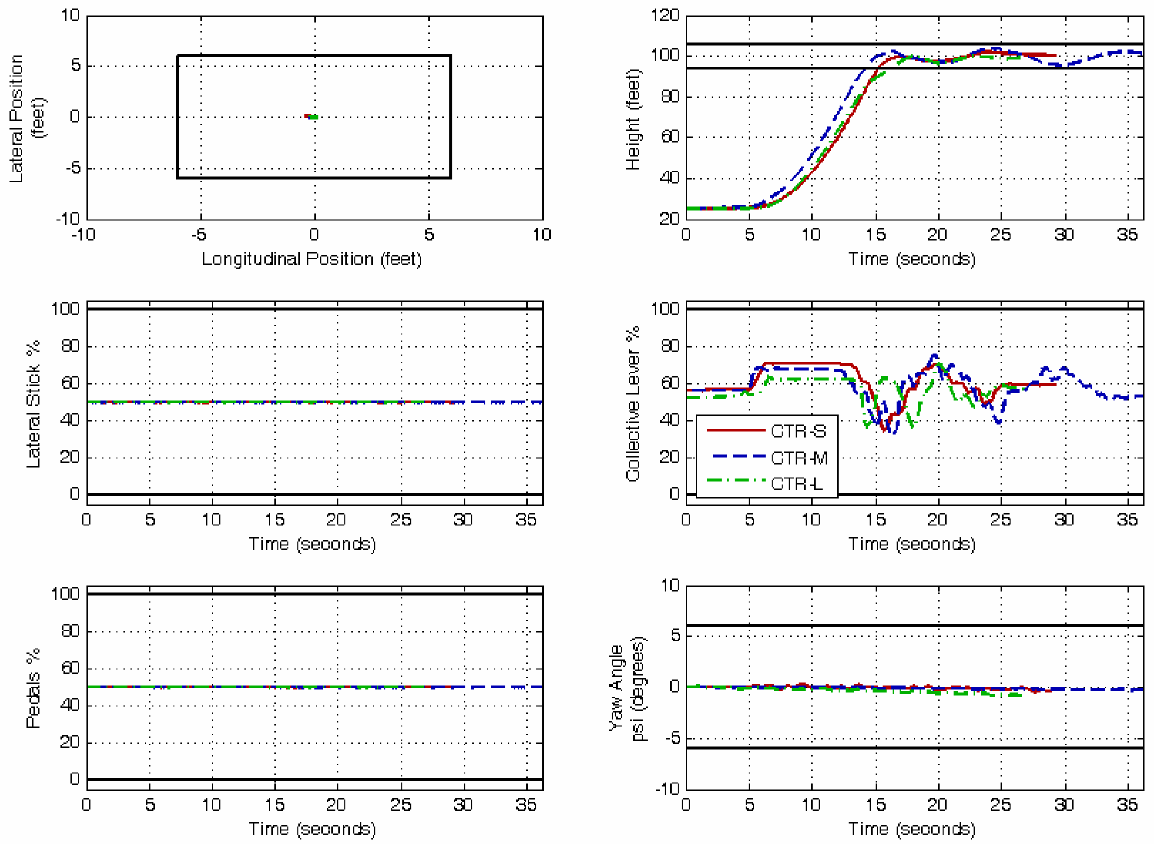


Figure 20: Bob up manoeuvres with 10% torque change at 10% thrust margin

5.4 Hover recovery

As with the pirouette, the hover recovery task requires a pilot to manoeuvre the aircraft in three axes at the same time. Here though, the axes of interest are pitch, roll and heave. Figure 21 illustrates an example of the performance in this task.

It can be seen that in each case, height control was poor, with the ADS-33 adequate performance requirements being approached and exceeded. This was due to the perception by the pilots that an increase in height was required during the manoeuvre, precluding the use of the altitude hold function. Both pilots observed that the visual cues available during this manoeuvre were quite poor, especially near the start point. Height cues are primarily provided by the hover board that marks the end point of the manoeuvre, and are not therefore immediately available to the pilot. The cones used to mark the required flightpath appear small at the start point of the manoeuvre and disappear from view when the pilot commences deceleration to hover. These cueing deficiencies tended to result in the pilots drifting forward of the designated course. Control activity was generally low, although a peak in lateral stick movement occurs following the deceleration to hover, while stabilising at the desired point. The control inputs required were essentially the same for each aircraft, indicating good unification of the handling qualities for this task.

At a 10% thrust margin, performance in this manoeuvre was poorer. This was because the pilots found they had to reduce their level of aggression in order to avoid exceeding 100% torque. This was reflected in the HQRs awarded for this manoeuvre, which were typically degraded by 1 compared with those at the standard weight. The agreement between the three aircraft holds, however.

For this difficult task, performance with no familiarisation time in the aircraft was generally poorer than otherwise. However, as a large part of this task is selecting the correct moment at which to commence the deceleration to hover, it is perhaps unsurprising if this timing was not quite correct on the one attempt allowed during this process.

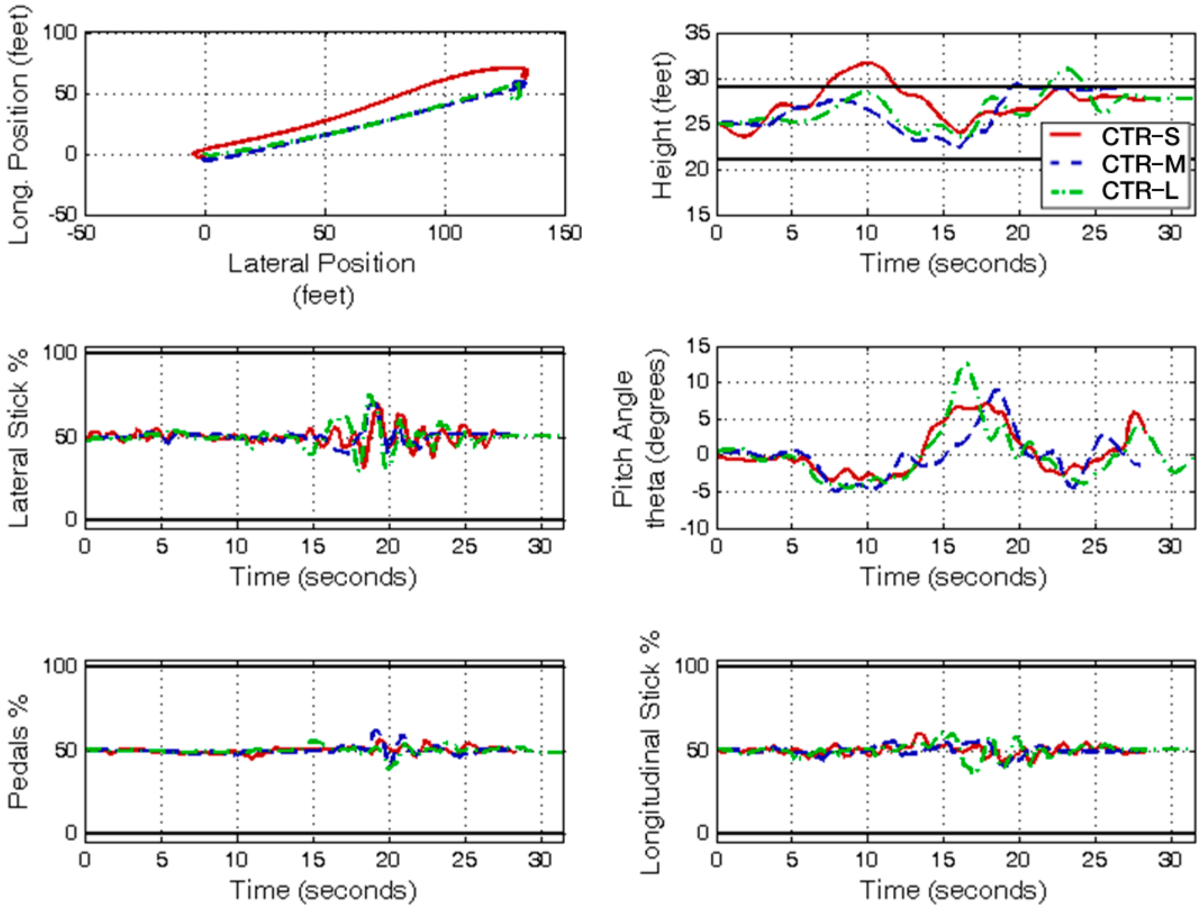


Figure 21: Hover capture

6. DISCUSSION

The hover turn MTE is predominantly a single axis yaw task, with assigned HQs well within the Level 1 region for all aircraft. This compares well with the predicted yaw axis HQs for non-tracking tasks. With an average yaw rate of 18°/s required for the 10 second turn, Level 1 control power for moderate agility manoeuvring is sufficient for this task. For the heading capture phase of the manoeuvre, yaw quickness becomes the relevant parameter, and comparison of the predicted HQs with the Level 1 ratings assigned for the hover turn manoeuvre suggests that the capture phase does not require the level of precision associated with tracking tasks – yaw quickness is Level 1 only for non-precision tasks.

The pirouette task is multi-axis, involving large amplitude yaw (>60° heading change), moderate amplitude roll (during the initial acceleration and final deceleration phases of the manoeuvre) movements, and with small amplitude corrections required throughout the manoeuvre in all axes. Performance in this task lies on the Level 1/2 boundary. Although Level 1 HQs were predicted for the primary non-tracking roll quickness and yaw control power components of the task, this was degraded by the degree of precision required to maintain longitudinal position. Although predicted HQs indicated Level 1 performance for pitch tracking tasks, the limited simulator field of view and lack of surface texture limited the pilots' ability to discern slight changes in longitudinal position, hence performance was degraded to Level 2 for this task.

All heave axis HQs were predicted to be Level 1, albeit marginally in the case of heave damping. The agreement between the predicted HQs and the assigned Level 1 results is therefore good.

The hover recovery task begins with the (non-precision) pitch and roll quickness prevalent to establish the required translational rate. This was a very low workload phase of the task, and was comfortably Level 1 for all aircraft. The end phase of the manoeuvre is again dominated by pitch and roll attitude quickness, followed by bandwidth in all axes while stabilising the hover at the correct position. The HQRs awarded for this manoeuvre were predominantly Level 1, which indicates that the stabilisation phase of the manoeuvre does not require the level of precision associated with tracking tasks.

In summary, the predicted and assigned handling qualities agree well for the tilt rotor aircraft with the model following controller. The MTEs flown did not, in general, contain precision tracking phases, as Level 1 performance was achieved even for those tasks requiring workload in areas where target acquisition and tracking performance was Level 2. However, the pirouette task did produce some Level 2 results, indicating that precise tracking was required to maintain accurate position. Figure 22 shows the comparison of the predicted and assigned HQs for the aircraft with the model following controller active.

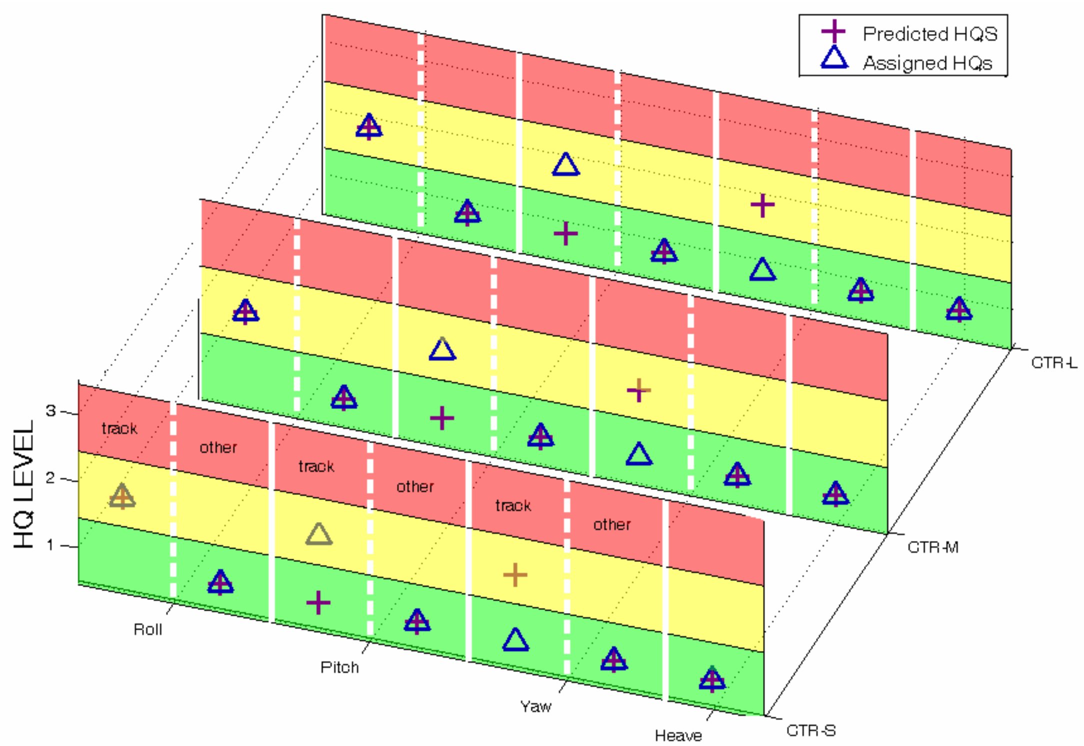


Figure 22: Comparison of Predicted and Assigned HQs for hover and low speed manoeuvring

7. CONCLUSIONS

In this, the second of two papers addressing the unification of handling qualities for a family of tilt rotor aircraft, the model-following controller technique has been used to augment the handling qualities of the aircraft discussed in the companion paper, [1]. The main conclusions of this study are as follows;

1. A model following controller has proved an attractive approach for ‘unifying’ the Handling Qualities of the three tilt rotor aircraft of different size and weight configurations, the desired HQs being ‘built into’ the prescribed model.

2. The controller has been successful in improving the HQs of the three tilt rotor aircraft to Level 1 for the ADS-33 hover and low speed criteria in the ‘all other MTEs’ category; the controller has effectively unified the HQs of the three aircraft for manoeuvres around the hover.

3. The assigned HQs agree well with the predicted HQs, with small differences showing up in the multi-axis manoeuvres, e.g. pirouette.

4. There is very little variation in the HQRs between the three aircraft for comparable manoeuvres.

5. The position-hold and altitude-hold systems have proven to be of significant benefit in reducing the workload required of the pilot, as expected.

6. Operation of the aircraft at higher weights appeared to have minimal impact on manoeuvre performance, with the exception of those cases where the aggression was reduced in order to avoid torque limit exceedances. The unification of the handling qualities of the three aircraft in low speed manoeuvres appears achievable at least down to thrust margins of 10%.

7. It was possible for the pilots to convert from one aircraft to another very quickly with minimal loss of performance.

8. Although unification has been achieved, for the larger aircraft this requires large control displacements in order to satisfy the Level 1 criteria; this is likely to result in control saturation and degraded HQs in more aggressive manoeuvres, when other augmentation solutions will need to be sought or a reduction in performance allowed.

9. The model following controller has been designed to operate in the low speed Helicopter Mode regime. Further work is required in order to extend it’s capabilities to the rest of the flight envelope, including the addition of extra control system functionality such as speed hold and turn coordination.

8. ACKNOWLEDGEMENTS

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