PILOT SENSITIVITY TO HANDLING QUALITIES-RELATED DESIGN PARAMETERS FOR A FUTURE PERSONAL AERIAL VEHICLE CONCEPT

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Abstract

This paper describes research underway at the University of Liverpool in the *myCopter* project to develop handling qualities guidelines and criteria for a new category of aircraft – the personal aerial vehicle, which it is envisaged, should demand no more skill than that associated with driving a car today. The focus of this paper is on assessing the sensitivity of 'flight naïve' pilots to changes in the characteristics of a translational rate command (TRC) response type and the force-feel of a traditional centre stick inceptor. The experiments identified an acceptable band of TRC velocity rise time characteristics to be between 2.5s and 5.0s. Only small variations in performance and workload were identified for changes in the force feel characteristics, although increased performance was noted with higher spring gradients.

NOTATION

ACAH	Attitude Command, Attitude Hold
GPDM	Generic PAV Dynamics Model
HMI	Human-Machine Interaction
HQs	Handling Qualities
PATS	Personal Aerial Transportation System
PAV	Personal Aerial Vehicle
PPL	Private Pilot's License
RCAH	Rate Command, Attitude Hold
TLX	Task Load Index
TPX	Task Performance Index
TRC	Translational Rate Command
TS	Test Subject
UoL	University of Liverpool
K_{lat}	Lateral stick to roll attitude gearing [°]
K_{trclat}	Lateral velocity pre-filter gain [m/s]
K_{vTRC}	Lateral velocity feedback gain [°/m/s]
P	Precision with which task is completed [%]
T_{trclat}	Lateral velocity pre-filter time constant [s]
T_{trclon}	Longitudinal velocity pre-filter time constant [s]
v_{horiz}	Vehicle lateral velocity [m/s]
$v_{horizcmd}$	Pilot's commanded lateral velocity [m/s]
W	Workload required to complete a task [1/s]
W_{min}	Theoretical minimum workload for a task [1/s]
δ_{lat}	Pilot's lateral control input
ζ_{lat}	Damping ratio of the lateral response
ϕ	Actual bank angle
ϕ_{cmd}	Commanded bank angle
ϕ_{TRC}	Bank angle command from TRC
ω_{lat}	Natural frequency of the lateral response

1. INTRODUCTION

Efforts are underway in Europe to define the enabling technologies that will make possible a revolution in air transportation – the Personal Aerial Vehicle (PAV)[1,2]. The *myCopter* project is studying the required vehicle and ground infrastructure (the Personal Aerial Transportation System, or PATS) technologies necessary for PAVs to operate safely in high traffic density regions (for example, PAVs converging on a small central business district during a morning rush hour). In addition, the project is examining the socio-economic issues surrounding the widespread adoption of PAVs to ensure that appropriate steps can be taken to mitigate the environmental and social impact of such a change. The project has three key research themes, which may be summarised as:

- Human-Machine Interaction (HMI), including cockpit technologies for inceptors and displays, and vehicle handling characteristics;
- Autonomous flight capabilities, including vision-based localisation and landing point detection, swarming and collision detection and avoidance;
- Socio-economic aspects of a PATS – the requirements for such a system to become accepted and widely adopted by the general public.

Within the first of these themes, the *myCopter* project is investigating the Handling Qualities (HQs) requirements for piloted flight[3]; identification of a suitable PAV cockpit configuration (including display symbology, inceptor type and inceptor feel characteristics)[4] and PAV pilot training requirements.

It is anticipated that the PAV might become a widely-used transportation method. For this to be feasible, the costs of purchase, training and operation must be lowered significantly in comparison to the equivalent costs of existing private light aircraft and helicopters – perhaps to a level similar to that associated with ownership and operation of a car today. If training costs (both initial and recurrent) are to be reduced, then it might be expected that the number of hours of training received by a novice pilot would be lower than that currently required to gain and maintain a Private Pilot's License (PPL) – a level that might be termed 'flight naïve'. One method by which this can be achieved is the application of autonomous capabilities to the PAV – removing from the pilot the need to manually fly the aircraft (the subject of the 2nd major research theme of the *myCopter* project[5]). However, it is anticipated that there may be scenarios (for example in the early days of PAV usage), where fleets of fully autonomous air vehicles are not technically feasible/acceptable to the public. In these cases, a (perhaps partially) manually piloted vehicle would be necessary.

It has been found in the research conducted to date[6] that it is possible for untrained PAV 'pilots' with a wide range of basic abilities to perform a series of hover and low speed manoeuvres with a vehicle configured to offer a Translational Rate Command (TRC) response type in each axis. In contrast, only the most able of the same group of 'pilots' could succeed with an Attitude Command, Attitude Hold (ACAH) response type, and only the most able of the 'pilots' could succeed with a Rate Command, Attitude Hold (RCAH) response type.

For each of the configurations described above, the vehicle's HQs were configured to be Level 1 according to the US Army HQ performance standard ADS-33E-PRF[7] – considerable research having been undertaken in the development of this document to ensure the provision of suitable HQs for extensively trained military pilots (and hence, not necessarily directly applicable to PAV 'pilots').

As with the HQ performance specifications, extensive research has been undertaken to determine optimum force-feel characteristics for different types of cockpit inceptors – both centre stick and side stick types have been the subject of recent investigations[8,9,10]. Again, however, this work has focussed on the perceptions of professional pilots, rather than PAV 'pilots'.

The purpose of the research described in this paper was to begin the process of identifying the sensitivity of PAV 'pilots' to changes in the configuration of a PAV simulation, in order to make recommendations that might contribute to a PAV design guide. In particular, the velocity characteristics of the TRC response type in the pitch and roll axes, and the force-feel characteristics of a centre stick control column have been investigated.

The paper begins with a description of the methodology that has been followed to determine PAV 'pilot' sensitivity for TRC response and force-feel characteristics; the results of piloted simulations are presented and discussed; and the paper is drawn to a close with conclusions and recommendations for continued research.

2. METHODOLOGY

2.1 Simulation Configuration

For the purposes of the experiments described in this paper, a Generic PAV Dynamics Model (GPDM), constructed in the Matlab/Simulink modelling environment, was used. The dynamic responses of the GPDM are derived through transfer function models of typical responses to pilot inputs. For the TRC response type selected for these investigations, the velocity response is the product of two separate stages. Firstly, an inner loop 2nd order transfer function provides an ACAH response to a command signal:

$$\frac{\phi}{\phi_{cmd}} = \frac{K_{lat}}{\frac{1}{\omega_{lat}^2}s^2 + \frac{2\zeta_{lat}}{\omega_{lat}}s + 1} \quad (1)$$

where:

ϕ - Actual bank angle;
ϕ_{cmd} - Commanded bank angle;
K_{lat} - Lateral stick to roll attitude gearing;
ω_{lat} - Natural frequency of the lateral response;
ζ_{lat} - Damping ratio of the lateral response.

Secondly, an outer velocity feedback loop converts this attitude response into a velocity response via the computation of a commanded bank angle/pitch attitude based on a desired flight speed:

$$\phi_{TRC} = v_{horiz_{cmd}} - \left(K_{v_{TRC}} \times v_{horiz}\right) \quad (2)$$

where:

ϕ_{TRC} - Bank angle command generated by the TRC outer loop;
K_{vTRC} - Lateral velocity feedback gain;
v_{horiz} - Vehicle lateral velocity (in plane parallel to Earth's surface);
$v_{horizcmd}$ - Pilot's commanded lateral velocity.

The desired flight speed is computed from a scaled, low-pass filtered, cockpit control deflection signal:

$$\frac{v_{horiz_{cmd}}}{\delta_{lat}} = \frac{K_{TRC_{lat}}}{\left(T_{TRC_{lat}}s+1\right)} \quad (3)$$

where:
δ_{lat} - Pilot's lateral control input;
K_{trclat} - Lateral velocity command pre-filter gain;
T_{trclat} - Lateral velocity command pre-filter time constant.

The output of this combination of ACAH inner loop and TRC outer loop is an essentially 1st order velocity response to a step cockpit control deflection, such as the example shown in Figure 1.

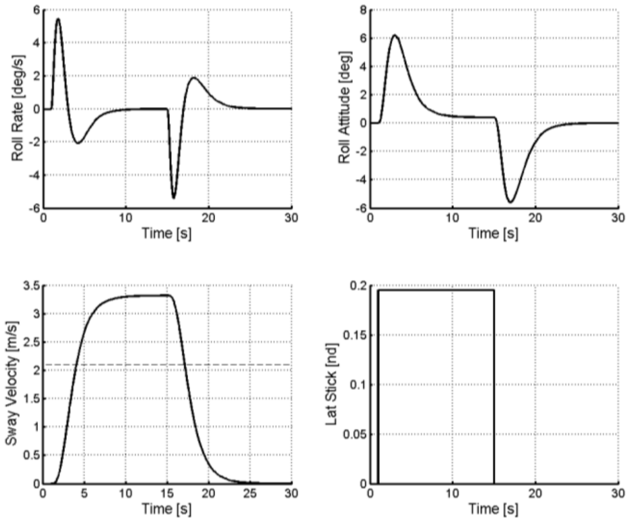

Figure 1: Translational Rate Response to Step Cockpit Control Deflection

The TRC response can be characterised by the 'rise time' – the time required to reach 63.2% of the final steady state velocity following a step control deflection. This is illustrated (for the acceleration phase) by the dashed horizontal line in the velocity subplot of Figure 1.

In the yaw and heave axes, direction hold and height hold functionality was implemented, removing the need to manually control these axes.

For the piloted simulation activities, the GPDM was implemented on the University of Liverpool (UoL) HELIFLIGHT-R flight simulator[11] (Figure 2). This simulator features a two seat crew station inside a projection dome, offering a high resolution, wide field of view outside world image. The dome is mounted on a six degree of freedom motion platform.


Figure 2: The HELIFLIGHT-R simulator at the University of Liverpool

Each seat in the crew station is equipped with a set of conventional rotorcraft controls (cyclic, collective and pedals), connected to a fully programmable force-feel system.

The dynamics of the force-feel system can be represented using a basic mass-spring-damper model, with the addition of an optional 'notch' at the neutral (zero spring force) position of the inceptor. The force required to break out of the notch can be user-specified.

2.2 Experimental Method

For both of the experiments described below, the general experimental method was the same. A number of 'flight naïve' pilots with a range of different backgrounds (see Section 3 – Results for details) flew a series of configurations of the GPDM in the HELIFLIGHT-R simulator in a hovering manoeuvre (derived from ADS-33E-PRF HQs practice). The precision achieved and workload were measured to objectively assess the compatibility of each GPDM configuration with the task. In addition, each 'flight naïve' pilot was asked to complete a NASA Task Load Index[12] (TLX) workload rating following the completion of each test point.

The manoeuvre is initiated from a stable hover and the vehicle is accelerated to a ground speed of between 6 and 10kts, at an altitude of 20ft. The target hover point is oriented approximately 45° relative to the heading of the aircraft. The ground track is such that the aircraft will arrive over the hover point. Upon arrival at the hover point, a stable hover should be re-captured and held for 30 seconds. The transition to hover should be accomplished in one smooth movement. It is not considered acceptable to accomplish most of the deceleration well before the hover point and then to creep up to the final position. The desired and adequate performance requirements for this task are shown in Table 1, with the 'flight naïve' pilots instructed to attempt to achieve the desired level of performance. The test course used in the piloted simulations is shown in Figure 3. Testing was conducted in a good visual environment and with nil-wind. For each configuration, each pilot flew the hover manoeuvre a number of times to learn how best to approach the task and to ensure a consistent level of performance had been reached. Typically, 4-5 runs were flown for each configuration. Note that in some cases, a configuration assessed early in the trial was repeated later in the test matrix to assess variability in the rating process and the sensitivity of the results to the experience gained by each pilot while completing these tests.

Table 1: Hover Manoeuvre Performance Requirements

Parameter	Desired	Adequate
Attain a stabilised hover within X seconds of reaching the target hover point	5	8
Maintain the longitudinal and lateral position within ±X ft of the target hover point	3	6
Maintain heading within ±X°	5	10
Maintain height within ±X ft	2	4

Figure 3: Hover Manoeuvre Test Course

Performance was measured objectively using the Task Performance Index (TPX)[6]:

$$TPX = \frac{P^2\sqrt{W_{min}}}{100^2\sqrt{W}} \qquad (4)$$

In the TPX, P is the precision, measured as the percentage of task time the pilot was able to spend within the task's desired performance tolerances. W is the workload, measured as the average number of discrete control inputs applied per second throughout the duration of the task. The TPX is normalised by a theoretical minimum rate of control activity, W_{min}, to produce a performance value between 0 (very poor performance) and 1 (perfect performance).

The Task Load Index is a workload rating system developed by NASA. It was designed to be applicable to the assessment of the workload involved in any task, and for it to be straightforward for new users to understand the concepts and processes involved in its use.

The TLX rating involves the assessment of six aspects of workload – mental demand; physical demand; temporal demand; performance; effort and frustration. The ratings for each of these aspects are then combined together using a weighting system, in which the test subject compares each of the workload elements to the other elements and decides in each case which represented the greater contribution to the overall workload of the task. This process allows a single workload score for each task to be produced. A TLX rating of 0 would be indicative of negligible workload, while a TLX rating of 100 would be indicative of the maximum perceived workload for the individual concerned.

2.2.1 Experiment 1 – Translational Rate Response Characteristics

The sensitivity of the test subjects to changes in TRC response characteristics was investigated by varying the value of the pre-filter time constants T_{TRClat} and T_{TRClon}. All other properties of the TRC outer loop and ACAH inner loop were held constant. To ensure harmonisation between pitch and roll axes, the responses were configured to always be identical to each other. Changing the value of the pre-filter time constant has the effect of altering the rise time of the velocity response following a step control input. A selection of the rise times assessed in this experiment is illustrated in Figure 4. In the experiment, the rise time was varied between 1.5 seconds to 11.5 seconds inclusive.

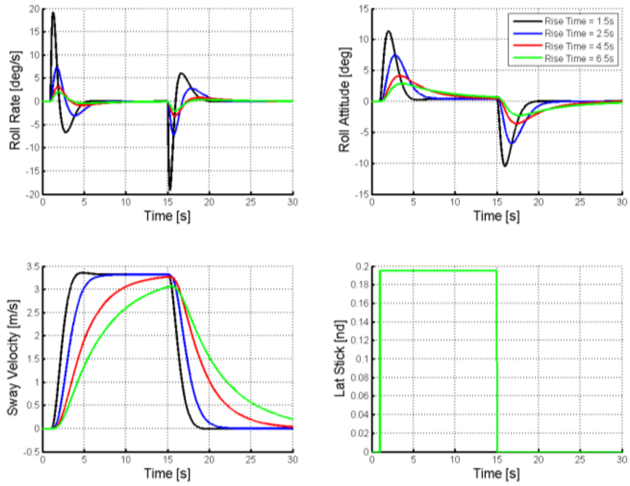

Figure 4: Effect of Adjusting TRC Rise Time

It can be seen in Figure 4 that changes in the rise time of the velocity response are created by changes in the magnitude of the initial roll/pitch rate following the control input, and hence the magnitude of the peak attitude change that results from a pilot input.

This characteristic of the changing response leads to an expectation that the results from this experiment should identify both an upper limit on TRC rise time, and a lower limit. The upper limit is a result of lengthening the time to reach a steady state velocity, requiring the pilot to anticipate the appropriate point to initiate a velocity change. This is especially important when there is a requirement to bring the vehicle to a hover at a precise location, as with the hover manoeuvre used in this investigation. Failure to correctly anticipate the point of deceleration leads to the pilot being forced to apply an increasing number of corrective (and potentially large magnitude) control inputs. At the other end of the scale, low TRC rise times become objectionable due to very abrupt vehicle responses which can be uncomfortable, and can destabilise the pilot-vehicle system via biodynamic feedback. Biodynamic feedback occurs when vehicle accelerations feed through the pilot's body and cause involuntary motion of the limbs, resulting in involuntary control inputs.

2.2.2 Experiment 2 – Cyclic Force-Feel Characteristics

Inceptor force-feel behaviour can be characterised through the device's *static* and *dynamic* behaviour. Dynamic behaviour is described using the natural frequency and damping ratio of a representative 2^{nd} order system. These properties can be related to the mass, spring force and damping characteristics used in the original force-feel model.

The focus of this experiment, however, is on the static behaviour of an inceptor. This behaviour is characterised through a breakout force, friction force, and spring gradient. Starting from the zero force position, when a pilot applies force to the inceptor, the friction in the system must be overcome. Following this, a high force gradient is encountered, meaning the application of considerable force for minimal displacement. This 'notch' provides the pilot with a positive confirmation that the control is centred (and in the case of the TRC response type, that a velocity of 0 is commanded). When the specified 'breakout force' is reached, the force gradient reduces and the control begins to move away from the zero force position. The lower force gradient is known as the 'spring force'; this typically acts to linearly increase the applied force with inceptor displacement until the maximum displacement is reached (the force applied by the pilot at the maximum displacement is known as the limit force).

If, at the point of maximum inceptor displacement, the pilot begins to reduce the applied force, initially the displacement will not change. This is due to the friction in the system – the pilot must first release the force used to overcome friction acting in the direction away from the zero force position, and then also overcome the friction acting in the direction towards the zero force position.

Once the friction has been overcome, the inceptor displacement reduces linearly with reducing force until the inceptor returns the breakout region, where the high force gradient returns.

Figure 5 illustrates a typical force-displacement chart that results from the interaction of the friction, breakout and spring gradient properties of an inceptor. The figure shows one of the sets of force-feel settings used during the experiment on the HELIFLIGHT-R simulator.

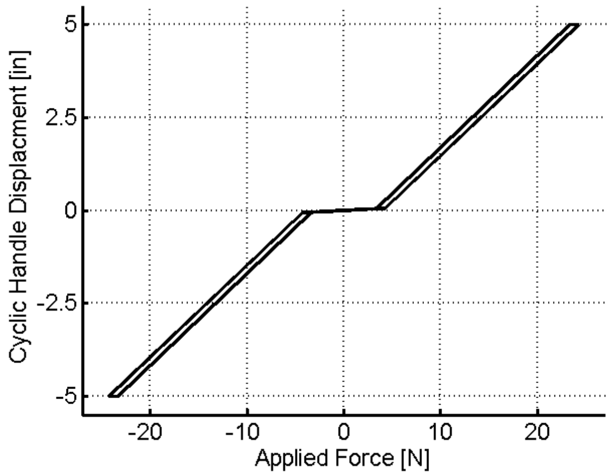

Figure 5: Typical Cyclic Handle Force-Displacement Chart

In the experiment, the impact of longitudinal cyclic spring gradients ranging from 0 N/in to 16 N/in was investigated for two different breakout forces (4.3N and 7.1N). The characteristics of the lateral cyclic were selected to maintain harmony with the longitudinal cyclic – for each setting, the lateral cyclic forces were 60% of the longitudinal cyclic force for the same displacement.

3. RESULTS

Three 'flight naïve' pilots have taken part in the evaluations for the experiments reported in this paper. Of these three test subjects (TSs), the first (TS1) has considerable experience flying in simulators such as the HELIFLIGHT-R, but has very limited flying experience in the real world. The second (TS2) has minimal simulator experience and no real world experience. Finally, TS3 holds a fixed wing PPL-A, and has approximately 160 flying hours, in addition to simulator experience in devices such as HELIFLIGHT-R.

3.1 TRC Rise Time

Starting with the experiment investigating the impact of TRC rise time on performance and workload, Figure 6 and Figure 7 show the typical impact on precision and control activity that moving from a low rise time to a high rise time has. The figures show a number of overshoots in plan position during the capture phase of the hover task with the higher rise time, accompanied by a significant number of corrective control inputs that are not present in the low rise time case. It is clear that the low rise time offers a more preferable result than the high rise time in this case.

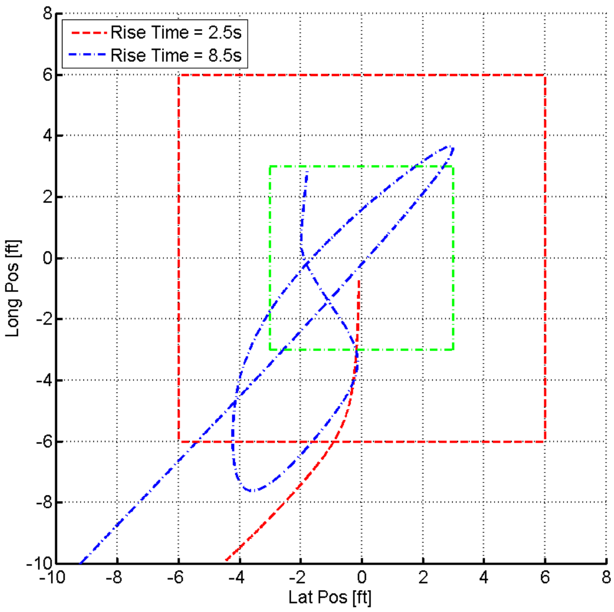

Figure 6: Impact of TRC Rise Time on Precision in Hover Manoeuvre

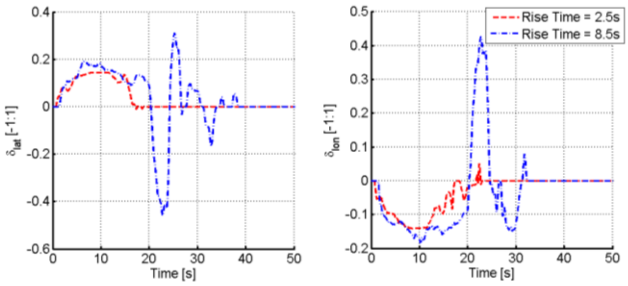

Figure 7: Impact of TRC Rise Time on Workload in Hover Manoeuvre

Moving to the analysis of the data from these tests, Figure 8 shows the TLX ratings awarded by each of the TSs after the final run with each configuration. Figure 9 shows the mean TPX score computed from all runs with each configuration, and Figure 10 shows the standard deviation of the TPX score across all runs for a given configuration.

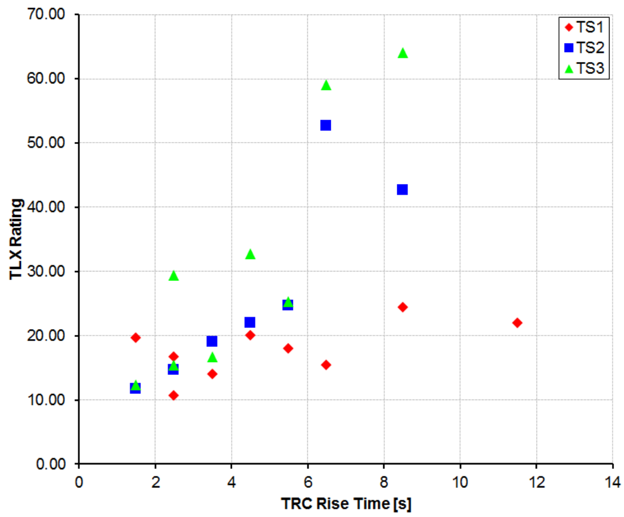

Figure 8: TLX Ratings Awarded for Range of TRC Rise Time Values

The results in Figure 8 show a reasonably consistent trend of increasing subjective workload as the rise time of the TRC response type increased, although the sensitivity of individual pilots to the change in rise time was variable. Two of the TSs repeated the rise time = 2.5s test point and in each case, their lower rating was awarded for the second attempt.

For the lower rise time values, the three TSs returned reasonably similar TLX ratings (spread of 5-10 points), with similar contributing factors, indicating that all three TSs experienced these test points in a similar manner. As the rise time increased beyond 6 seconds, however, the spread in ratings increased significantly, with TS1 reporting a much lower level of subjective workload for these test points than either TS2 or TS3. TS1 also reported an elevated level of workload in the rise time = 1.5s case compared to the rise time = 2.5s case. This was due to the increased amount of mental effort required to slow the movement of the cyclic handle and hence reduce the 'sharpness' of the vehicle response with this very short rise time.

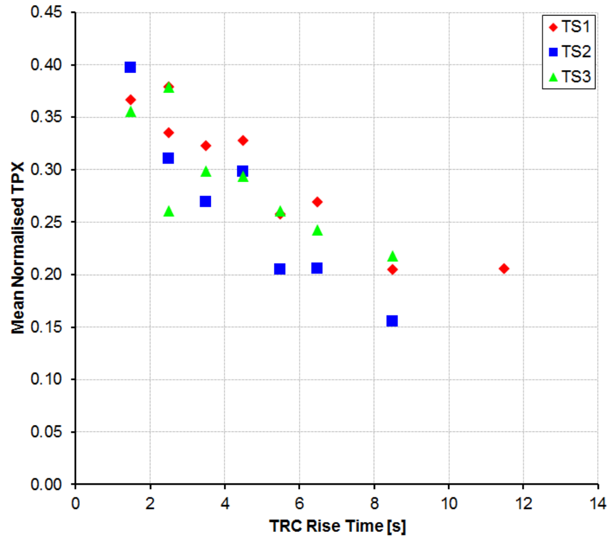

Figure 9: Mean TPX for Range of TRC Rise Time Values

Figure 9 shows a consistent reduction in TPX score as the TRC rise time increases. This correlates well with the increase in subjective TLX rating found in Figure 8. For this metric, all three TSs returned results that indicate similar levels of sensitivity to the change in response, and there was no significant change in this trend at any level of rise time.

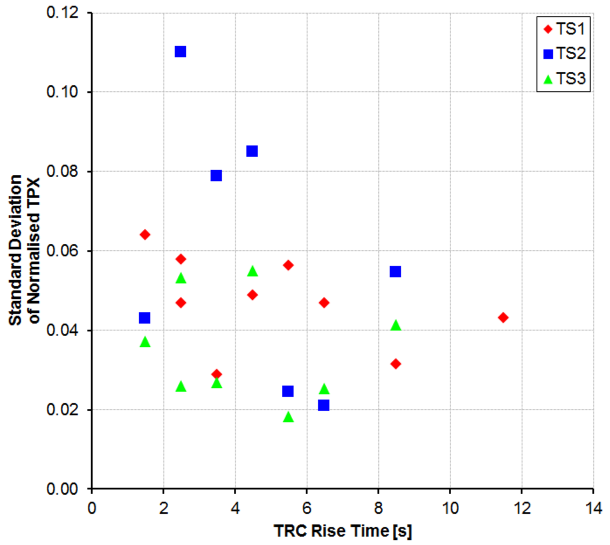

Figure 10: Standard Deviation of TPX for a Range of TRC Rise Time Values

While the TLX and mean TPX results are indicative of the absolute level of performance that is achievable for a given configuration, the standard deviation results shown in Figure 10 indicate the level of inter-run consistency that was achieved for each configuration. This is a potentially important aspect of the recommendation of vehicle handling characteristics, as the achievement of a repeatable level of performance can be a key factor in ensuring the safety of the vehicle and its pilot.

Figure 10 shows a much greater level of variation between the three TSs than the previous analyses. In particular, the results for TS2 typically show higher standard deviations and a greater level of scatter between the configurations, while the results for TS3 typically show lower standard deviations and less scatter from configuration to configuration. This result is perhaps a function of the different levels of experience of each of the TSs.

Looking at the results for TS3, a pattern of lower standard deviations can be seen for TRC rise time values between 2.5 and 6.5 seconds. The results outside this band show a significantly higher standard deviation. Results for the other TSs are less clear, but it may be seen that there is a similar dip in the standard deviation result for TS1 in the band between 2.5 and 4.5 seconds. The results for TS2 are, however, contradictory to those for TS1 and TS3, with the highest standard deviations being measured in the 2.5s to 4.5s band.

3.2 Cyclic Force-Feel

The TLX ratings for the cyclic force-feel experiment are shown in Figure 11 (for the lower breakout force) and Figure 12 (for the higher breakout force). These figures show a slight preference from the TSs for lower spring gradients and also for a lower breakout force. The trend here is not, however, as clear and strong as was the case in the first experiment with the TRC rise time.

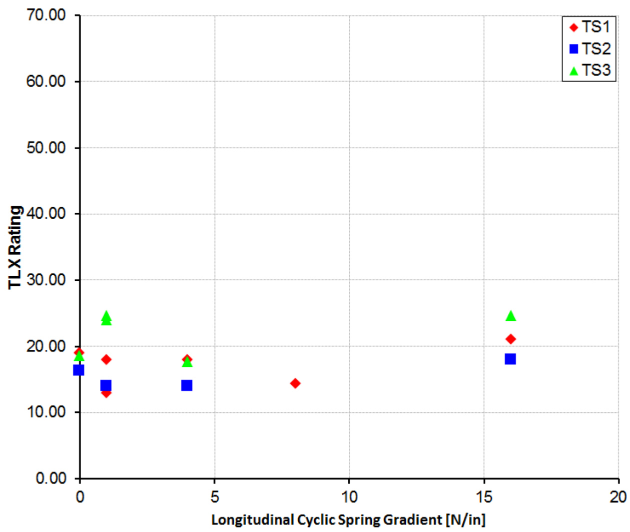

Figure 11: TLX Ratings Awarded for Range of Spring Gradient Settings with Breakout Force = 4.3N

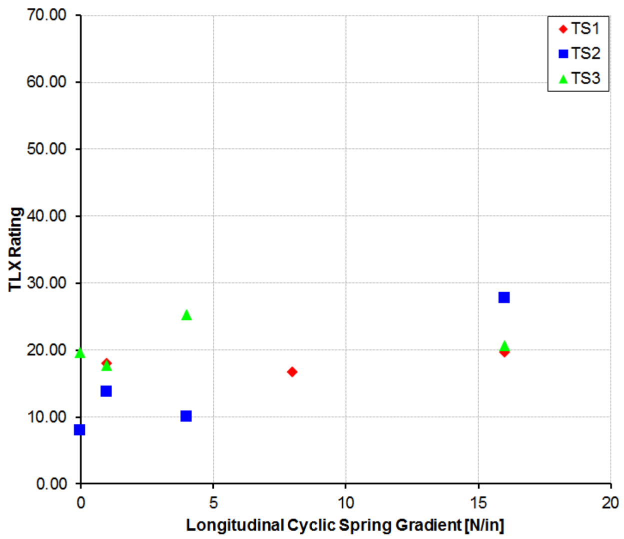

Figure 12: TLX Ratings Awarded for Range of Spring Gradient Settings with Breakout Force = 7.1N

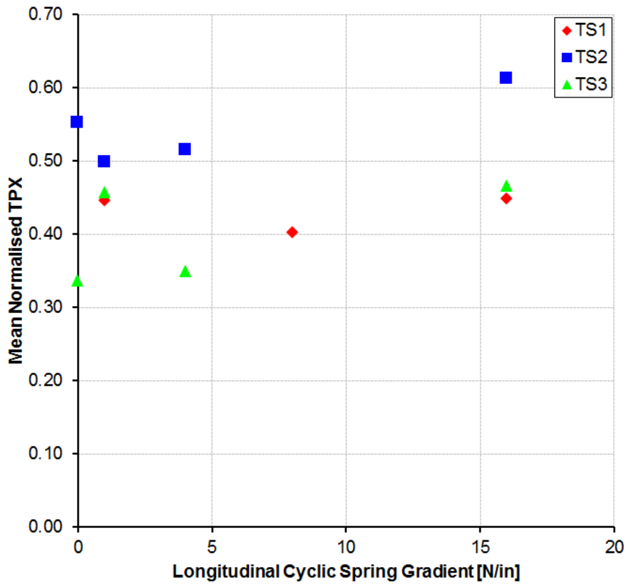

Figure 14: Mean TPX for Range of Spring Gradient Settings with Breakout Force = 7.1N

The averaged TPX scores from all attempts at a particular configuration are shown in Figure 13 for the lower breakout force and Figure 14 for the higher breakout force. These figures show that the TSs were typically able to achieve a better level of performance (higher TPX) with the higher spring gradient settings, and also with the higher breakout force.

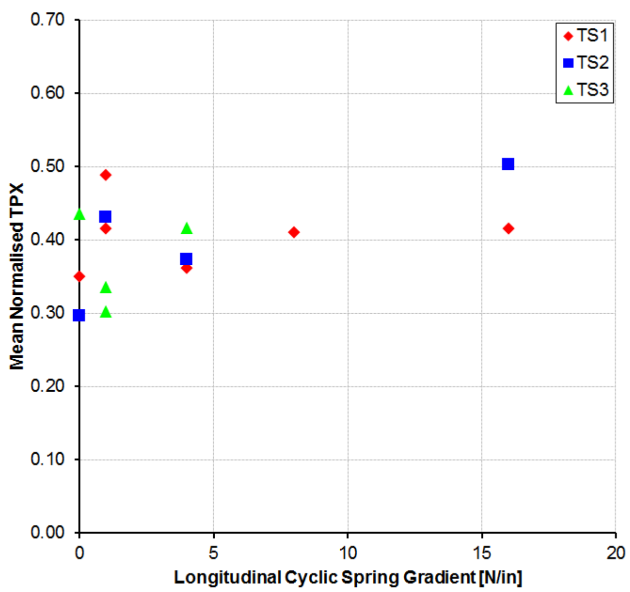

Figure 13: Mean TPX for Range of Spring Gradient Settings with Breakout Force = 4.3N

In the first experiment there was a good level of agreement between the TLX and TPX results, but this is not the case here. These apparently contradictory results are a product of the 'physical demand' component of the TLX rating. The description of 'physical demand' used to guide test subjects in the completion of a TLX rating is:

> "How much physical activity was required (e.g. pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?"[13]

While the actual displacements of the controls may be similar with low and high cyclic forces, the effort required of the pilot to make those movements is progressively greater as the cyclic forces increase. This leads to higher physical demand scores, and also to an increase in the relative importance of the physical demand to the overall workload.

Removing the physical demand component from the TLX calculation gives the results shown in Figure 15 (for the low breakout force) and Figure 16 (for the high breakout force). These results show a much closer correlation with the TPX scores in Figure 13 and Figure 14 than was the case with the overall TLX ratings.

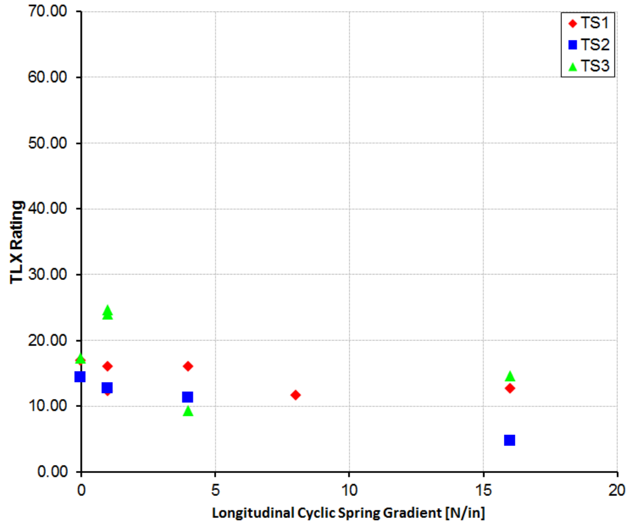

Figure 15: Adjusted TLX Ratings with Breakout Force = 4.3N

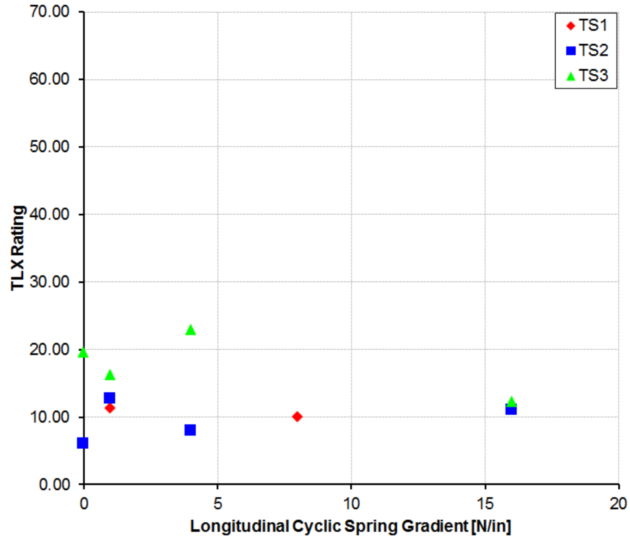

Figure 16: Adjusted TLX Ratings with Breakout Force = 7.1N

It has been seen that the TSs were able to achieve better performance in the hover task with higher cyclic forces, and the TLX ratings (minus physical demand) show agreement with this. However, the level of physical effort required to complete a task is very important, and a pilot cannot be expected to fly for long periods of time with very high control forces, as they will fatigue quickly – hence the high physical demand scores in the TLX ratings. Therefore, a band of acceptable control forces must be identified that offer a combination of good performance and sufficiently low effort for prolonged operations.

Turning to inter-run consistency, the plots of the standard deviation of TPX for the tested spring gradients are shown in Figure 17 (for the low breakout force) and in Figure 18 (for the high breakout force).

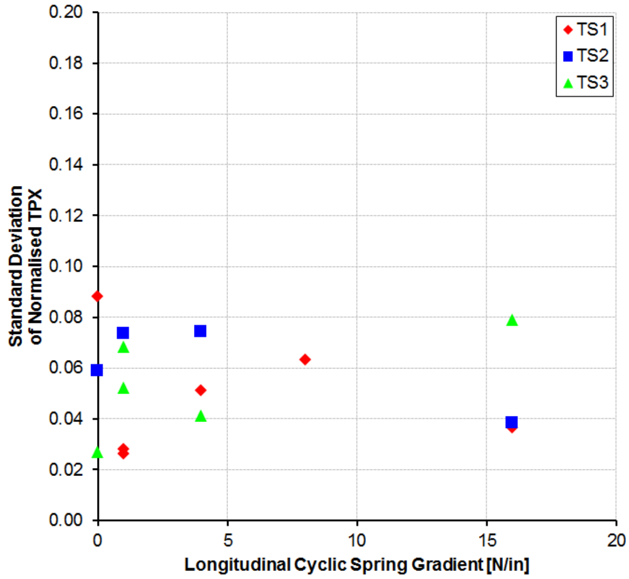

Figure 17: Standard Deviation of TPX for a Range of Spring Gradient Settings with Breakout Force = 4.3N

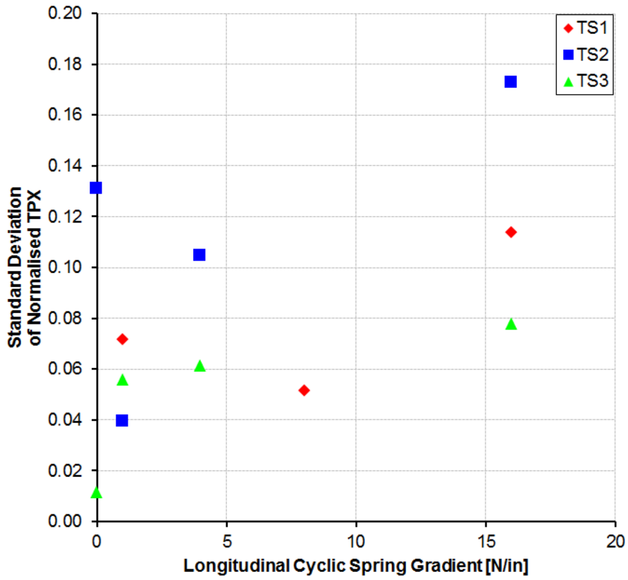

Figure 18: Standard Deviation of TPX for a Range of Spring Gradient Settings with Breakout Force = 7.1N

Examination of Figure 17 and Figure 18 reveals little in the way of significant trends as the spring gradient changes. In some cases, the TS was able to achieve their best consistency with a low spring gradient, while in others, higher spring gradients resulted in increased consistency. One clear result can be seen, however, in a comparison of Figure 17 to Figure 18. The lower breakout force shows a typically reduced standard deviation of TPX compared to the higher breakout force – for all TSs and across all spring gradient settings. Furthermore, there is noticeably less spread between the TSs in the case of the lower breakout force – a result that can also be seen in the earlier figures for TLX and mean TPX.

4. DISCUSSION

The results presented above permit an evaluation of the suitability of the assessed TRC response and cyclic force-feel characteristics for use on a PAV by flight-naïve pilots.

In the case of the TRC rise time, the captured objective and subjective ratings indicate that the lower rise times result in a better level of performance at a lower workload. The standard deviation of the TPX score (calculated across all runs attempted with a particular configuration) also suggests agreement with these findings – a greater amount of run-to-run variability being found with longer rise times. However, the standard deviation analysis also reveals an increase in run-to-run variability at very low rise times. This was also seen in the commentary provided by the test subjects – although all TSs generally liked the very rapid response and ease with which high precision could be attained when testing the low rise time configurations, they commented on the poor ride comfort and potential for disorientation and destabilisation that could arise from the high roll and pitch rates. It should be noted that these comments were received in simulation, using a device with a relatively short-stroke motion platform. If the motions experienced in the simulator were scaled up to the real world, it might be anticipated that these effects would be commensurately stronger.

Combining the pilots' comments with the increased standard deviation allows the placement of a lower limit on TRC rise time between 2.0 and 2.5 seconds.

For the upper limit, a steady increase in TLX is accompanied by a steady reduction in TPX as the rise time increases. The previously reported research showed that TLX ratings less than 25-30 typically correspond to acceptable levels of workload, while the TPX score should be greater than 0.25. Applying these constraints places the upper limit on TRC rise time in the 5.0 to 5.5 seconds region. The analysis of the standard deviation of the TPX scores of individual runs agrees with this finding – for both TS1 and TS3 a rise time of 5.0 to 5.5 seconds is close to the point where their run-to-run variation begins to increase.

These findings can be compared to the requirements for military helicopters provided in ADS-33E-PRF[7]. This requirement states that, to be acceptable, the rise time of the TRC response (in pitch and roll) must be between 2.5 and 5.0 seconds. There is therefore a good level of agreement between the requirement for military rotorcraft pilots, and the findings in this paper for potential PAV pilots. This is a perhaps unsurprising but nonetheless significant result.

Turning to the cyclic force-feel experiment, trends with changing spring gradient are much less clear than in the TRC rise time experiment. In terms of the acceptability criteria discussed above, all of the spring gradient settings would be acceptable, with relatively low workload and high performance. This finding is perhaps indicative of a general insensitivity to spring gradient characteristics for the tested manoeuvre, especially when the underlying vehicle dynamics are highly optimised. There is, however, a clear indication that the lower of the two investigated breakout force settings is preferable – with generally lower TLX ratings and higher TPX scores, and reduced inter-run variability in comparison to the higher breakout force setting.

To facilitate comparison with the requirements for military rotorcraft in ADS-33E-PRF, Table 2 shows the ranges of acceptable values for breakout force, spring gradient and limit force for Level 1 handling.

Table 2: Longitudinal Cyclic Static Force Requirements in ADS-33E-PRF

Criterion	Min. Value	Max Value
Breakout Force (N)	2.2	6.7
Spring Gradient (N/in)	2.2	13.4
Limit Force (N)	N/A	67

In terms of breakout force, the results above are in good agreement with the ADS-33E-PRF requirements. The lower breakout force of 4.3N is within the acceptable band, while the higher breakout force of 7.1N lies just outside the acceptable band.

For the spring gradient, the tested configurations span and exceed the upper and lower limits shown in Table 2. The relative lack of variation seen in the results, even well outside the ADS-33E-PRF Level 1 regions, confirms the requirement to assess additional manoeuvres before a firm recommendation can be made regarding the suitability of specific cyclic spring gradient settings for a PAV.

5. CONCLUSIONS

This paper has described two investigations into the sensitivity of flight-naïve pilots to changes in the characteristics of a simulated Personal Aerial Vehicle.

The first investigation examined the effect of changing the velocity rise time property of a translational rate command (TRC) response type in the pitch and roll axes. The second examined longitudinal and lateral force-feel characteristics for a conventional centre-stick control column. The tests were conducted using a hover manoeuvre in a good visual environment with nil-wind.

The conclusions related to the preferences of flight-naïve pilots that can be drawn from this work are as follows:

- Very low TRC rise times give rise to poor ride quality and the potential for disorientation and destabilisation.
- Large TRC rise times give rise to poor predictability and consequent reduced levels of precision and elevated workload.
- A band of TRC rise times between 2.0-2.5 and 5.0-5.5 seconds provided a good compromise between rapid response and smooth ride for all of the test subjects. This is the recommended range in which the TRC response should be located for a PAV.
- The band identified above agrees very closely with that specified for military pilots in ADS-33E-PRF, indicating commonality of perception of good TRC handling characteristics for professional and flight-naïve pilots.
- For the inceptor breakout force, the test subjects showed a preference for the lower of the two tested values, with lower TLX ratings and improved run-to-run and inter-test subject consistency.
- Higher spring gradient settings allowed the test subjects to perform the hover manoeuvre with a greater level of precision. However, the higher resultant forces are fatiguing and give rise to an increase subjective workload. For the hover manoeuvre, no clear picture emerged of a preferable band of spring gradient settings.
- ADS-33E-PRF places clear upper and lower limits on acceptable spring gradients. This suggests that the hover manoeuvre is insensitive to variations in inceptor force-feel characteristics, at least when flown with a vehicle exhibiting an optimised TRC response type.
- Further testing with additional manoeuvres is required in order to confirm the findings regarding the TRC rise time characteristics, and to continue the process of identifying inceptor force-feel characteristics.

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