EVALUATION OF ROTORCRAFT PILOT INDUCED OSCILLATIONS (PIO): RESULTS FROM A DLR/NRC COLLABORATIVE PROJECT

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Abstract

Pilot-induced oscillations (PIOs) still pose a significant risk to safety of rotorcraft operations, particularly as no formal evaluations are conducted during test and evaluation programs. Usually during experimental flight testing if PIOs are observed, additional testing and evaluations are conducted. This paper details results from a joint research effort undertaken by researchers at the National Research Center Canada (NRC) and the German Aerospace Center (DLR) to investigate and test novel methods and techniques to assess PIOs occurring in rotorcraft. The efforts included modifications to test processes and the use of PIO detection and prediction criteria. The research was conducted using both a ground-based simulation facility and a research helicopter. Results of the campaign showed the suitability of a novel subjective assessment scale and a PIO detection algorithm. This was confirmed through both objective and subjective assessment. Furthermore, modifications to ADS-33 mission task elements were also considered to improve the applicability to testing for PIOs.

NOTATION

ACT/FHS	Active Control Technology/ Flying Helicopter Simulator
ACG	Attitude Command (Good Handling Qualities)
ACP	Attitude Command (Poor Handling Qualities)
ADS	Aeronautical Design Standard
APC	Adverse Pilot Coupling
A/RPC	Aircraft/Rotorcraft Pilot Coupling
AVES	Air Vehicle Simulator
BPD	Bandwidth Phase Delay
DLR	Deutsches Zentrum für Luft und Raumfahrt (Eng. German Aerospace Center)
FBW	Fly-by-Wire
FCS	Flight Control System
HQ(R)	Handling Qualities (Rating)
HQL	Handling Qualities Level
MTE	Mission Task Element
NRC	National Research Council Canada
OLOP	Open-Loop Onset Point
PAC	Phase Aggression Criteria
PIO	Pilot-Induced Oscillation
PIW	Pilot-Inceptor Workload
PVS	Pilot-Vehicle System
RC	Rate Command
RLE	Rate Limiting Element

1. INTRODUCTION

Aircraft/Rotorcraft Pilot Couplings (A/RPCs) are defined as adverse, unwanted phenomena originating from anomalous and undesirable couplings between the pilot and the vehicle [1]. The term encompasses all unfavourable vehicle responses that result from pilot control actions, whether active or passive, within the control loop.

The most recognized form of A/RPCs is the pilot-induced oscillation (PIO). This refers to an oscillatory response which is characterized by an active pilot attempting to control the aircraft, unfavourable and undesirable aircraft response of the vehicle, and a trigger event which causes the oscillations. PIOs have been cited as a factor in a number of fatal accidents during flight testing, including the fatal loss of the AW609 [2].

In contrast to other handling qualities (HQ) aspects, there are no robust and defined methods to test for PIO tendencies. Usually during experimental flight testing if PIOs are observed, additional testing and evaluations are conducted. If PIOs are not exposed during testing, no additional investigations are undertaken. This implies that causal conditions associated with PIOs will be exposed during testing. A large amount of research has been conducted to date for fixed-wing vehicles [1]. However, specific rotorcraft investigations are limited.

To investigate methods to detect, predict, and evaluate PIOs, the German Aerospace Center

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(DLR) and the National Research Council Canada (NRC) embarked upon a collaborative project. The project was separated into two phases; Phase I was conducted at DLR research facilities and Phase II was conducted at the NRC. At DLR, a simulation campaign was conducted in the Air Vehicle Simulator (AVES). At NRC, the Bell 205 Airborne Simulator was used for investigations. These facilities are discussed later in the paper.

1.1. Research Goals

The following were the goals of the research campaign;

- To determine the suitability of mission task elements (MTEs) to expose rotorcraft PIOs, both in simulation and flight test campaigns.
- To conclude upon the usability and applicability of the Adverse Pilot Coupling (APC) scale for in-flight and pilot-in-the-loop simulation investigations.
- To further validate phase aggression criteria (PAC) PIO susceptibility boundaries using new tasks, vehicles, and pilots.
- To provide a broad range of PIO characteristics and responses to validate objective and subjective assessment methods.

To achieve these goals, two dedicated test campaigns were undertaken. Firstly, a simulation campaign was conducted in Germany at DLR facilities in Braunschweig using the Air Vehicle Simulator (AVES) between 3rd – 7th December 2018. A subsequent flight test campaign was conducted in Canada at NRC Flight Research Laboratory facilities in Ottawa using the Bell 205 Airborne simulator in March 2019.

1.2. General Approach

Test techniques were adopted from HQ investigations, namely the use of subjective pilot opinion scales (incl. APC scale) and the use of previously defined mission task elements (MTEs). The same test techniques were used both in the simulation and flight test campaigns. A number of previously tested MTEs were used for the campaigns. Simulation Campaign

The investigations were limited to two types of well-known and investigated PIOs, namely,

- Category I (Cat. I): linear type oscillations, usually caused by system delays.
- Category II (Cat. II): quasi-linear type oscillations, usually caused by saturation or rate limits within the pilot control channel.

The root cause of the PIO is referred to as the ‘trigger’ [1]. Throughout the campaigns, simple PIO triggers were used (i.e. time delays, rate limits) in order to simplify the analysis of resultant PIOs. It is however acknowledged that PIOs within modern fly-by-wire aircraft are often caused by complex interactions between the pilot and flight control systems (so-called Cat. III oscillations, e.g. mode switching, parameter blending, etc.).

Two pilots participated in the test campaigns, one from each organisation. Both pilots involved were experimental test pilots. In the campaign conducted at the DLR AVES facility, both pilots completed evaluation runs. In the flight test campaign conducted at NRC, Pilot A acted as the safety pilot throughout, and Pilot B was the evaluation pilot. Due to time constraints, it was not possible for Pilot A to complete any additional evaluation runs.

The paper proceeds as follows. Firstly, the test and evaluation tools used in both phases of the project are presented. These include both tools to predict PIO incipience, to detect and assess PIOs, and methods to subjectively assess PIO. Secondly, Phase I of the project, tests at DLR facilities are discussed. Following, Phase II of the project, tests conducted at NRC facilities are discussed. A final discussion of the results is presented, along with conclusions and recommendations for future research efforts.

2. TEST AND EVALUATION TOOLS

This section describes test and evaluation tools used during both the simulation and flight test campaigns. It was the intention during the investigations to use the same assessment and evaluation tools, to allow eventual comparison between simulation and flight tests.

2.1. Offline Prediction Tools

‘Offline’ describes tools used during pre- or post-processing of data collected from piloted tests. This is opposed to ‘on-line’ or real-time assessment tools, which are used during the piloted test. Two offline prediction methods were used to assess PIO incipience prior to the pilot simulation/flight trials; bandwidth phase delay (BPD) and the open-loop onset point (OLOP). Both of these methods have previously been applied to rotorcraft. For completeness, both methods are briefly described in the following subsections.

2.1.1 Bandwidth Phase Delay

Bandwidth phase delay is a method that has been previously applied to both fixed-wing and rotary-wing analysis, and is subsequently contained within ADS-33 [3]. It is used to assess linear response dynamics of the vehicle (i.e. Category I PIOs).

BPD gives a general indication of vehicle HQs. In ADS-33, corresponding predicted handling qualities levels (HQL) are provided for a range of missions and rotorcraft types. Its validity is extended to roll, pitch, and yaw dynamics within hover and low speed, and to roll and pitch for forward flight cases.

Previous studies investigating the potential for PIOs during rotorcraft flying tasks have shown a correlation between lateral target tracking and acquisition boundaries and PIO incipience [4]. It is likely not coincidental that these boundaries have strong similarity to those used to assess PIO for fixed-wing aircraft. Furthermore, a number of previous studies have used the fixed-wing boundary directly, whereby a good correlation with experimental result has been shown [4-5]. These boundaries are shown later in the paper and are valid for both longitudinal and lateral dynamics. The vehicle will be PIO prone if the phase delay, τ_p, is greater than 190ms. This is independent of bandwidth, ω_{BW}. Furthermore, PIO is possible if either $\tau_p > 0.14$ s and/or $\omega_{BW} < 1$ rad/s.

Minor differences in the calculation of BPD exist depending on whether the system response is a rate command system or attitude command (attitude hold) system. Two “bandwidth” values are defined in ADS-33; the gain bandwidth and phase bandwidth. Information regarding the calculation of these parameters is contained in ADS-33 [2]. ADS-33 also states that, for attitude command systems, if the gain bandwidth is smaller than the phase bandwidth or if the gain bandwidth is indeterminate, the rotorcraft may be PIO prone for high precision tasks or during tasks requiring aggressive pilot technique.

2.1.2 OLOP criterion

The open-loop onset point (OLOP) criterion was proposed by Duda [6], as a method to determine incipience to Cat. II (quasi-linear) PIOs due to rate or position limiting elements. As discussed later in this paper, investigations regarding Cat. II oscillations for rotorcraft were only conducted during the simulation campaign at DLR facilities. OLOP was originally developed for use on fixed-wing aircraft, but has since been applied to rotorcraft applications [7].

OLOP determines potential PIO incipience through analysis of the pilot-vehicle system (PVS). At the time of its conception, PIO analysis was commonly conducted using linearised aircraft models. Using only linearised models, quasi-linear response due to rate limiting elements (RLEs) was not observed. The method is based upon the use of describing functions to approximate RLEs in the system. RLEs can be described by the input amplitude and a so-called open onset frequency (ω_{OLOP}). This is the frequency where the RLE is ‘activated’ for the first time at the current input amplitude.

Research in [6] showed that the activation of RLEs leads to a rapid increase in phase distortion. This is referred to as a ‘phase-jump’. Observing the frequency and dynamics at the point where the phase jump occurs allows one to determine whether the activation of RLEs has the potential to cause Cat. II PIOs. Using an extensive database of fixed-wing Cat. II PIO events, Duda defined a boundary to determine PIO susceptibility using a Nichols chart. This boundary is shown in Figure 1, with an illustrative example of the OLOP results. The Cat. II PIO incipience is determined based on the position of the OLOP. If the OLOP is above the boundary, the configuration is considered PIO prone. For the example shown in Figure 1, the green line represents a PIO robust case and the red line represents a PIO prone case.

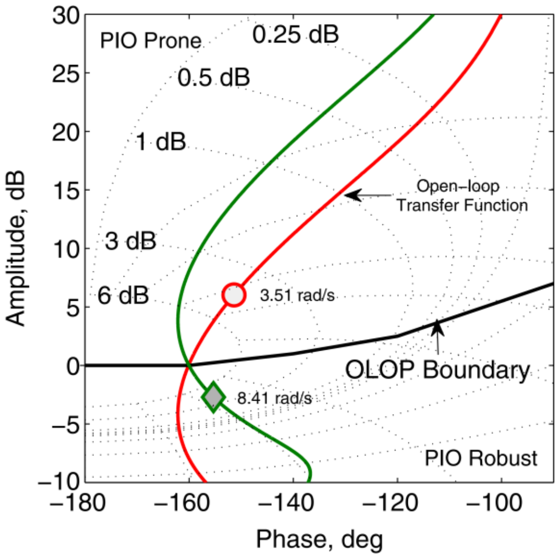

Figure 1: Example of OLOP boundaries and results displayed for four sample data cases

OLOP has a number of advantages when investigating rate limiting. Firstly, it can be applied during linear analysis of control systems, typically employed during the development phase. Secondly, it can be applied to RLEs at different points in the Flight Control System (FCS). RLEs both in the forward and feedback control paths can be analysed. Thirdly, the criterion accounts for changes in pilot-vehicle dynamics due to the FCS.

A number of studies, examples including those detailed in [5, 8-11], have used OLOP for analysis with varying success. OLOP has previously been used both during research campaigns and to investigate known cases where PIOs have occurred (e.g. YF16). In [8], it was recognised that using ADS-33 criteria and linearised models could lead to very high system bandwidth, which was initially found to tune the roll and pitch axis command model bandwidths to meet HQL 1 requirements. When evaluating Sikorsky H-53 helicopter model with dynamics relative to these bandwidth criteria for the first time in the vertical motion simulator (VMS), RLEs of the actuator models were reached, and the pilots had difficulty flying the system. Divergent PIOs occurred at the end of one test run and pilots commented that the vehicle was very PIO sensitive, uncontrollable and quick to diverge. Post analysis of the system was conducted using OLOP and the susceptibility of the system was confirmed.

In a number of other research efforts [4, 6-9], the boundary proposed has been found to be over conservative. For this reason, a number of modifications to its use have been proposed, including the removal of a ‘pilot model’, a modification to the susceptibility boundary (shift by +5dB) and the reduction of control inputs used to calculate ω_{OLOP}. Removing the pilot model is only acceptable for RLE in the FCS and not for RLE at the pilot input [6], and only limited data is currently available to justify shifting the OLOP boundary.

The reduction of control input magnitude for the OLOP process was proposed in [12], and tested at various flight speeds and conditions. In this research, results suggested that the use of the maximum control input led to conservative predictions, which did not reflect the pilot activity during piloted ADS-33 mission task elements (MTEs) or during normal operation of the vehicle. As a result, it was proposed that OLOP is applicable during normal pilot activity or inceptor deflection.

Based on conclusions and recommendations made in previous efforts discussed above, two modifications to the OLOP method were made in the current investigation. Firstly, a more realistic and representative pilot model was used in this analysis, whereby the simple gain model previously used was replaced with the Hess structural model [13]. This model incorporates neuromuscular dynamics, control inceptor dynamics and vestibular feedback, all of which have been found to influence the susceptibility of the vehicle to PIO [4-5]. Furthermore, the method of tuning the model to determine a pilot vehicle crossover dependent upon frequency rather than based upon crossover phase is more appropriate for rotorcraft applications.

A second modification was to use representative pilot control inputs, as found in investigations detailed in [12].

The modifications to OLOP and detailed discussions regarding the application and differences with respect to the previous applications were presented in a previous publication [14]. The reader is directed towards this publication for more detailed information.

2.2. Detection tools for Piloted Flight/Simulation

This section describes detection tools used to support and supplement data collected from pilot-in-the-loop tests. Two methods were used in this research effort. The PAC is a real-time capable detection algorithm, to determine whether PIOs are occurring/have occurred. The objective method can be used to support traditional data inspection and analysis. The Adverse Pilot Coupling (APC) scale is a novel method to collect pilot subjective opinion.

2.2.1 Phase Aggression Criteria (PAC)

During the campaign it was of interest to further validate the PAC, a real-time detection tool for identifying PIOs. Boundaries developed in previous investigations were found to be suitable for rotorcraft without complex flight control feedback, and featuring rate-command type response only.

The PAC is a real-time capable method developed to detect PIOs in-flight. It was originally conceived only as an analysis tool. However, it was shown through results that the method could be used as a prediction or early warning system, to mitigate against severe and extreme PIOs, those which could result in catastrophic failure or loss of control. The PAC method was originally based upon the pilot-inceptor workload (PIW) theory proposed by Gray [14]. PIW builds a two dimensional picture of the pilot control input response, by evaluating the pilot activity (duty cycle) and the pilot aggression. In various publications, the definition of aggression differs, however it is always a general measure of the input magnitude and rate of control inputs. The duty cycle is defined as the time for which the pilot is considered to be active. The PIW can be either time varying (whereby one time step must be defined) or can be the result of the complete evaluation run.

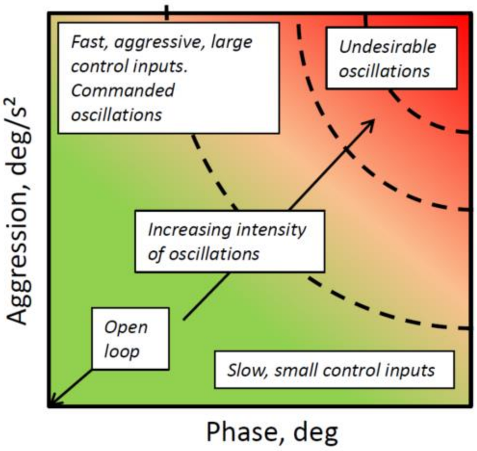

Figure 2: Schematic of phase-aggression criteria

PIW alone is not sufficient to observe whether PIOs occur during the flight, as there is no consideration for the vehicle output. Through definition, a mismatch between pilot and vehicle must exist [1]. For this reason, PAC extends PIW by including information regarding the phase distortion between the pilot input and the vehicle output. A schematic of the PAC is shown in Fig. 6.

The methods to calculate PAC phase and aggression parameters are contained in a number of previous publications, including [16]. For this reason, it is not described here again in detail. The aggression (A_G) was calculated using Eqn. (1),

$$A_G = H_s \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \left| \dot{\delta}_{\theta_{1c(1s)}}(t) \right| dt \tag{1}$$

where t_1 and t_2 are the start and end time of the current oscillation respectively, $\dot{\delta}_{\theta_{1c(1s)}}$ is the rate of change of the control input, and H_s is a scaling parameter. The scaling parameter H_s was defined as the steady state rate (primary axis) due to a perturbation in position (or force) of the control inceptor, approximated using Eqn. (2),

$$H_s = \frac{\Delta p(q)}{\Delta \delta_{\theta_{1c(1s)}}} = \frac{\Delta \theta_{1c(1s)}}{\Delta \delta_{\theta_{1c(1s)}}} \frac{\Delta p(q)}{\Delta \theta_{1c(1s)}} \tag{2}$$

where $\Delta p(q)$ is the change in roll (pitch) rate and $\Delta\theta_{1c(1s)}$ is the change in control swashplate angle. As in previous research, in this study H_s has been approximated as a constant value for each of the control configurations. The reader is referred to [16] for further information regarding the calculation of the PAC.

2.2.2 Subjective Pilot Opinion: Adverse Pilot Coupling Scale (APC)

Two methods were used to assess PIOs during the campaign; a legacy PIO scale [17] and the APC scale. The APC scale was presented in [16] and has been developed to account for known limitations in the legacy PIO scale. It is shown in Figure 3. This scale has been developed and tested using flight simulation, and at the time of the test campaign, had not been used in-flight. As the APC scale has not yet adopted universally for PIO investigations, PIO ratings with the legacy rating scale were also taken. Ratings from both scales were compared to ensure consistency. In addition, handling qualities ratings (HQR) were awarded to determine whether large changes in task performance occurred, or whether configurations experienced 'cliff-edge' type HQ characteristics.

3. SIMULATION CAMPAIGN

This section describes the simulation campaign conducted at DLR facilities. The goal of this campaign was to collect a range of data from different PIO conditions and tasks, in order to,

- characterise different types of PIOs which may occur in future rotorcraft
- to determine the cases of most interest for planned flight test campaign at NRC in 2019.

3.1. Test Set-up

The test plan for AVES campaign intentionally included a broad range of control configurations and tasks. Due to cost and safety considerations, the simulation facilities at DLR were used to investigate a broad range of PIO conditions and tasks. It was also planned to test the most interesting of these cases using NRCs Bell 205 aircraft.

AVES (shown in Figure 4) is maintained and operated by DLR. Its design pivots around the ability to easily interchange aircraft cockpits for use on a single motion platform. Currently, the facility features one fixed-wing cockpit (Airbus A320) and one helicopter cockpit. The latter, shown in Figure 5, is a replica of the Active Control Technology/Flying Helicopter Simulator (ACT/FHS). During the test campaigns conducted in this research, AVES was used without the use of the hexapod motion platform.

The simulation uses both hardware and software used in the ACT/FHS, including the FCS software and active control inceptor sidesticks.

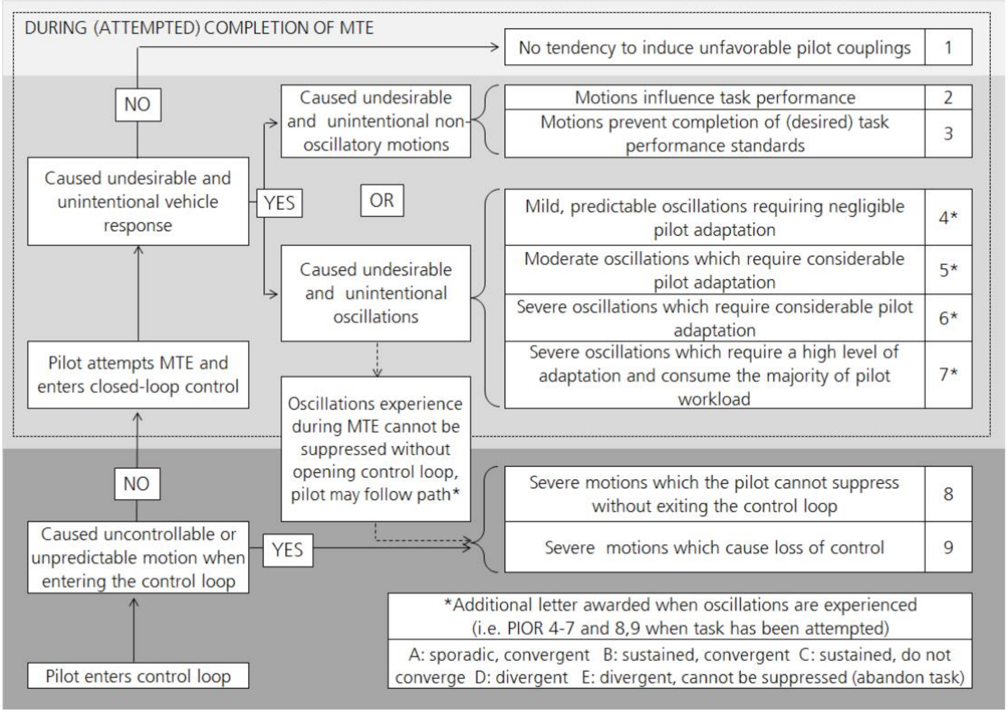

Figure 3: Adverse Pilot Couplings (APC) scale

Figure 4: Air Vehicle Simulator (AVES) located at DLR, Braunschweig

Figure 5: Simulation Cockpit of Active Control Techology/Flying Helicopter Simulator (ACT/FHS)

3.2. Configurations and Tasks

During the trial, a simulation model of DLRs ACT/FHS aircraft was used. This experimental aircraft is highly modified version of the Airbus EC-135 helicopter. As a result, its response and the incipience of the vehicle to PIOs does not reflect the production type helicopter.

To provide a range of PIOs during the campaign, three different control systems were used. One of these systems featured a rate command response type (RC), whilst the other two featured attitude command response types, one with good HQs (ACG) and one with poor HQs (ACP). These were determined prior to the test campaign during exploratory tests with one of the test pilots.

All configurations were set using a Proportional Integrator Differential (PID) controller used for in-flight investigations in the ACT/FHS. Test points were conducted in a random order. To allow the pilots to correctly control the aircraft, they were made aware of the vehicle response type before completion of each manoeuvre. Additional classical PIO triggers were added. These were intentionally kept simple, to help with the analysis of any incurrent PIOs.

The pilots were not briefed on the PIO triggers used, nor were they informed of changes during the simulation campaign. Table 1 shows the added delays and rate limits used during the investigation.

Table 1: Command systems, delays and rate limits used in the campaign.

Command	Delay (ms)	Rate Limits (%/s)
FHS RC	0, 200,300,400	35,17,10
FHS ACG (Good HQs)	0, 200, 400	35,17,10
FHS ACP (Poor HQs)	0, 200, 400	100,35,17

The rate limit is measured as percent per second of maximum actuator travel. For example, 100%/s refers to a rate limit whereby the actuator can be displaced by 100% in either direction within one second without experiencing limiting. Delay is added to the actuator input, to simulate a delay from the flight control system or control mechanical hardware.

Figure 6 shows the BPD results with respect to control configuration and for three time delays; 0ms, 200ms and 400ms. An increase of time delay causes a reduction in bandwidth for all cases. Results are shown with respect to the PIO boundary (thick solid and dashed lines) initially proposed from fixed-wing research. Also shown are ADS-33 target acquisition and tracking boundaries. These are shown as light dashed lines. These boundaries are dependent on control axis.

During the campaign, five mission task elements (MTEs) were selected, completed by both test pilots. These were selected to expose the range of operational tasks performed by rotorcraft. Table 2 shows the MTEs selected and the primary reason for their use.

Table 2: Selected MTEs including reason for use and modifications required.

Task	Reason for use	Modifications
Depart Abort	Longitudinal PIO incipience	None
Lateral Reposition	Lateral PIO incipience	Achievable ground speed
Hover	Lateral and Longitudinal	Transition speed
Pirouette	Lateral PIO incipience	None
Tracking task	Lateral PIO incipience	None

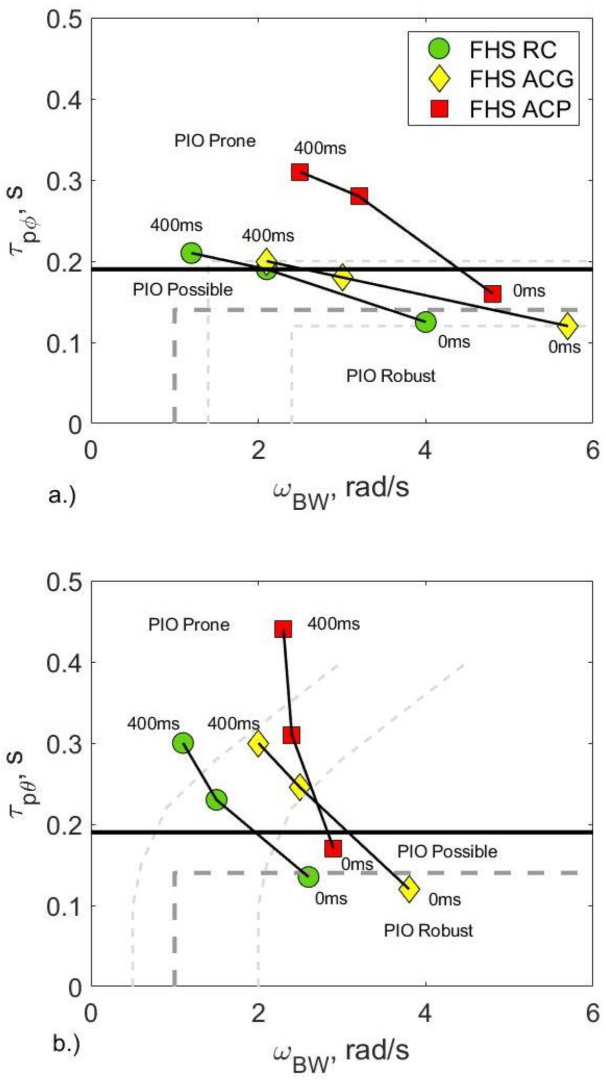

Figure 6: Bandwidth phase delay results for control configurations flown in the Air Vehicle Simulator test campaign. a) roll axis and b) pitch axis.

A number of tasks and associated performance standards were taken directly from ADS-33 [1]. The advantage of this approach is that the standard performance requirements are known and acknowledged as representative. These tasks result from testing conducted to ascertain suitable levels of aggression. The standardised nature of the tasks assists to compare results from this research effort with previous investigations. Both the Depart Abort and Pirouette manoeuvre were completed using performance standards directly from ADS-33, for cargo/utility aircraft.

The Hover and Lateral Reposition manoeuvres were also taken from ADS-33, but it was necessary to modify the performance requirements for the investigation. The Lateral Reposition manoeuvre performance standards were found to be too aggressive for the vehicle type (ACT/FHS), and therefore it was required to reduce the maximum desired ground speed during the translation. This led to lateral translations that the pilot believed were suitably aggressive to perform the task safely (and would subsequently be acceptable for in-flight investigations).

The Hover manoeuvre was modified to increase the aggression. When completing the task using tolerances and performance requirements as given in ADS-33, the aggression was found to be too low to expose PIO deficiencies. This reflects results found in previous research [16]. In the previous work, the aggression of the manoeuvre was increased by reducing the distance between the helicopter and the hover position reference marker. This increased the aggression during the stabilised hover element of the task. For this investigation, it was not possible to modify the visual database. As a result, the task aggression was increased by increasing the translation speed. Rather than completing the manoeuvre with a translational speed of 6-10 knots, a speed of 13-17 knots was selected. Pilots stated during the investigation that this clearly increased task aggression without leading to unrealistic performance standards.

All tasks from ADS-33 were conducted using a specifically built test course, featuring ground and reference markers. This course allows pilots to assess their performance during the completion of the task through the use of external cues. An example of the visual references and the course layout is shown in Figure 7, for the Pirouette manoeuvre.

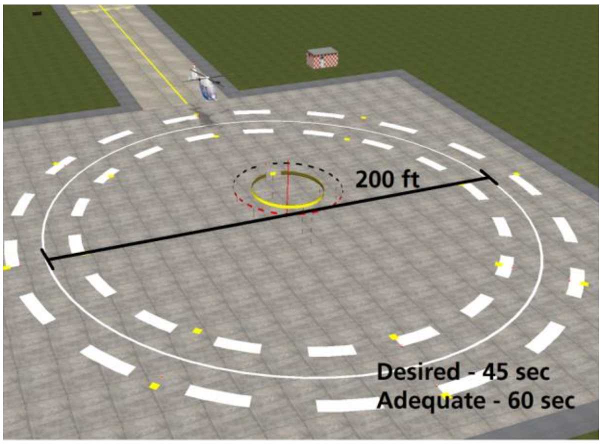

Figure 7: Example of ADS-33 test course used in the Air Vehicle Simulator (Pirouette MTE)

An additional roll tracking task was conducted to investigate lateral dynamics during forward flight. Various PIO research efforts have employed a variety of tracking tasks, which combine changes in flight attitude and stabilisation periods [5, 11]. The task used in this investigation was developed during work discussed in [18] and incorporates both tracking and stabilisation elements. An example of the tracking task signal is shown in Figure 8.

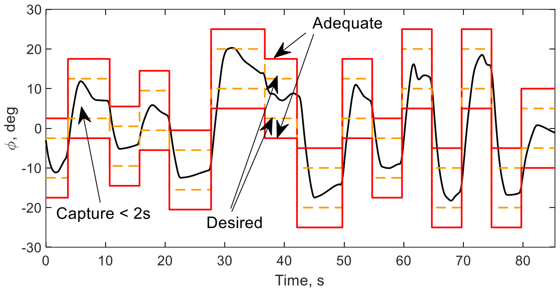

Figure 8: Tracking pattern used within the Air Vehicle Simulator (AVES)

Each run consisted of 14 attitude changes. Two patterns were used so that the pilot could not memorise the required trajectories. The task required the pilot to maintain a forward flight speed of 60kts and to use a head down display, shown in Figure 9.

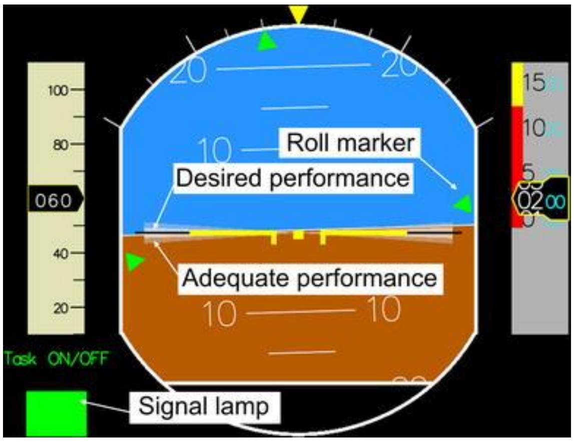

Figure 9: Roll tracking HDD used within the Air Vehicle Simulator (AVES)

Using the artificial horizon, a desired attitude was displayed to the pilot. Pilots were required to capture the desired attitude within 2 seconds in order to achieve the task. This was set as a requirement to force pilot aggression. Once the attitude was captured, pilots were required to keep within desired (or adequate) attitude tolerances until the next change in desired attitude. An additional view was available for the Flight Test Engineer, which was also used following each run to analyse performance.

The aircraft was trimmed in this condition prior to each run. The pilot was required to maintain forward speed throughout the run. To maintain realism, no axes were fixed. Desired vehicle attitudes were between 5° and 10°. For desired performance, pilots were required to maintain a roll attitude ±5° and for adequate performance ±10°. The pilots generally commented that the task was suitable and representative of aggressive forward flight manoeuvring.

3.3. Results

This section shows some examples of the results obtained during the campaign.

Both pilots completed all manoeuvres. Generally, the manoeuvres were found to successfully expose PIOs, of varying magnitude and severity. The nature of the PIOs experienced however were found to be dependent upon the task conducted. This was a result of the task performance requirements. In the following sections some example results are shown from each of the tasks completed. All test cases, APC and PIO ratings are shown in the Appendix.

Lateral Reposition Manoeuvre

During the completion of the Lateral Reposition task, PIOs were exposed on a number of occasions during the stabilization element of the task. Only PIOs in the lateral axis were experienced. One example of a severe PIO experienced during the task is shown in Figure 10. This was the most severe PIO event experienced during the completion of the manoeuvre. During this case, the pilot commented that full control deflection was required, and at point during the manoeuvre he was not in control of the aircraft. As a result, the pilot awarded HQR = 10. The use of maximum control travel is confirmed in Figure 10. As a result, large roll oscillations occur, to a maximum of 40°. As a result of the severity of the oscillations, which led him to abandon the task during the attempted completion, the pilot awarded APC = 9E. As shown in the data trace, rate limiting has occurred during the periods of high control input magnitude.

Figure 11 depicts the PAC results for the case. As shown, most of the PAC points are within the “No PIO” region. Severe PIO is detected during the point of maximum control input and maximum aggression. This was the point that led to the HQR and APC ratings that the pilot awarded. Therefore, the PAC results are consistent with the pilot comments.

Pirouette

Similarly, to the Lateral Reposition manoeuvre, a number of severe PIOs were experienced during the stabilization element of the task. These were experienced by both pilots. On a number of occasions, these led to the pilots abandoning the task. In addition, during several runs longitudinal PIOs were also experienced during the cases with rate limiting. This was unexpected prior to tests. These oscillations developed during the translational element of the task, resulting in maximum magnitude during the stabilisation element of the task. Furthermore, on occasion, the pilots abandoned the task prior to the stabilisation element.

Due to the vehicle dynamics, the pilot was required to correct the ground drift in the longitudinal axis. As the pilot was primarily concentrating on controlling the lateral axis to complete the translation, he was concentrating more on this aspect than controlling the longitudinal drift. As a result, a build-up of oscillations occurred, subsequently materialising in some cases as divergent.

This showed that the task can successfully be used to expose PIOs in multiple axes. In these cases, this was demonstrated for the lateral and longitudinal axes.

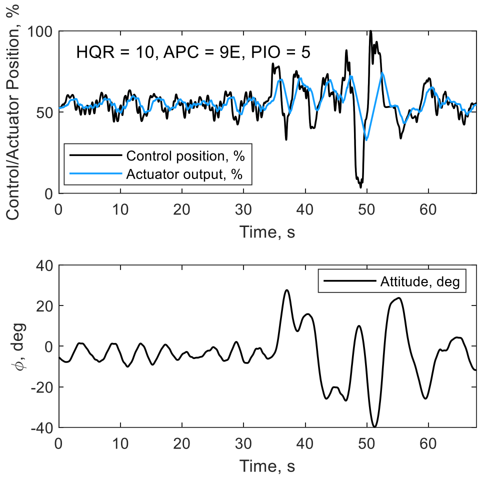

Figure 10: Data trace during the completion of the Lateral Reposition, RC, RL 17%/s, Pilot A

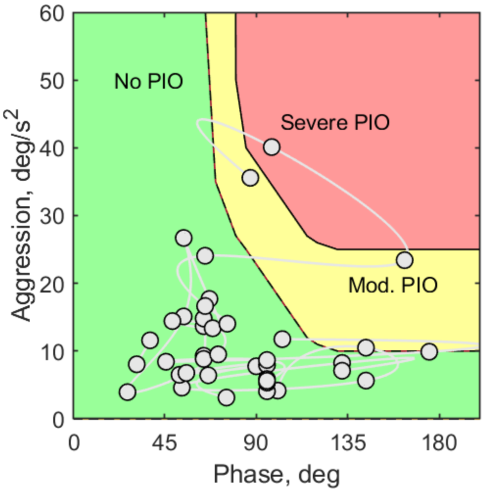

Figure 11: Results of Lateral Reposition task in the Phase Aggression Criteria (PAC), RC 17%/s

Hover manoeuvre

The Hover manoeuvre also successfully exposed PIOs for a number of configurations. Unlike the Lateral Reposition, the Hover task led to higher frequency PIOs. This is due to the task requirement to maintain precise positioning following the transition element. An example of a persistent PIO in the lateral axis is shown in Figure 12. Here, high frequency oscillations develop and continue throughout. The pilot commented that at some points the oscillations required him to essentially abandon the task. The divergent nature of oscillations is shown between 70 s to 80 s. HQR = 6 was awarded as the pilot believed that adequate performance was maintained, despite periods where the pilot was actually not attempting to maintain this performance.

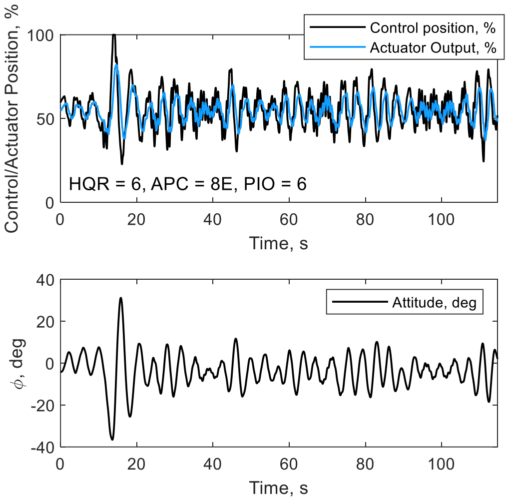

Figure 12: Data trace during completion of hover manoeuvre, lateral axis, RC 400ms time delay, Pilot B

Figure 13 shows the PAC results for this case, from the lateral axis. As shown, points were found within all regions of the chart. A number of points were found within the Moderate and Severe PIO regions. This supports the feedback from the pilot.

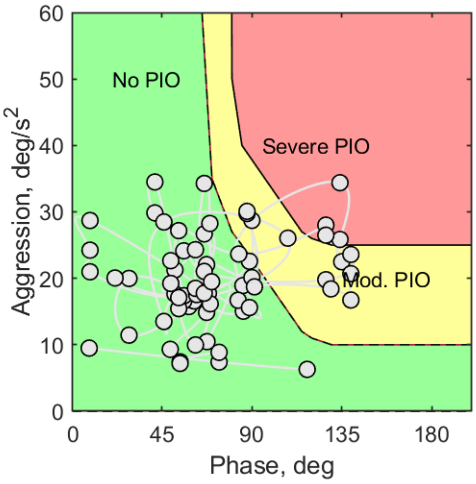

Figure 13: Results of Hover task in the Phase Aggression Criteria (PAC)

Roll Tracking Task

Some of the most enlightening results were found during completion of the roll tracking task. Due to the single nature axis of this task, it was easier to isolate the PIO axis, unlike some of the ADS-33 MTEs. Furthermore, the task allowed for repeatability. For this reason, it was possible to clearly see differences in pilot strategy.

One example is shown in Figure 14 and Figure 15. These two cases were completed using the same configuration (ACG) flown by different pilots.

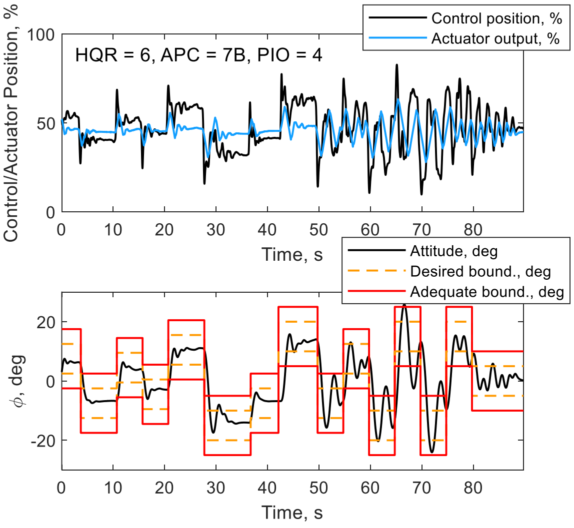

Figure 14: Tracking task, Attitude Command (Good Handling Qualities), RL 17%/s, Pilot A

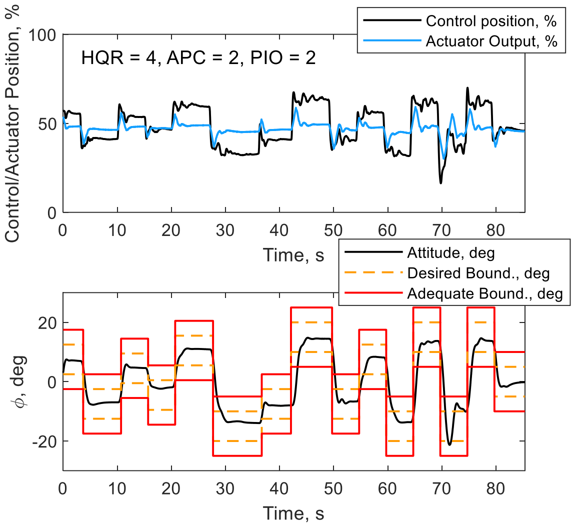

Figure 15: Tracking Task, Attitude Command (Good Handling Qualities), RL 17%/s, Pilot B

For the first half of the task, both pilots avoided any visible PIOs. However, at approximately 50 seconds, Pilot A initiated an abrupt control input which led to visible oscillations. These continued throughout the remaining segment of the task. Pilot B significantly reduced his control inputs following all large changes in attitude. Using this strategy, task performance was maintained and PIOs were avoided.

Further examples are shown in Figure 16 and Figure 17. Figure 16 shows results for the configuration above (ACG) with an added 400ms time delay. This led to uncontrollable oscillations throughout, and severe divergent (show through the APC and PIO ratings). Figure 17 shows the same case completed by Pilot B. Here, the pilot uses the same strategy as in the previous case, and minimizes the control inputs following large transitions. The pilot is able maintain desired performance.

In this case, the pilot awarded HQR = 5 due to deficiencies. However, no oscillations were apparent, and the pilot was able to attain desired performance throughout.

Comparison with Prediction Criteria

Figure 18 shows a summary of results obtained for the cases where only time delays alone were applied. No large differences were observed between longitudinal and lateral dynamics, as in previous studies, and therefore both are plotted together. APC ratings awarded are also shown. The PIO boundary from fixed-wing research, which has been shown to be applicable to rotorcraft, is used as guidance.

As expected, results indicate a correlation between phase delay and PIO incipience and subsequent severity. The most severe PIO was found for the highest phase delay. Within the "PIO possible" region, a number of mild PIOs were recorded.

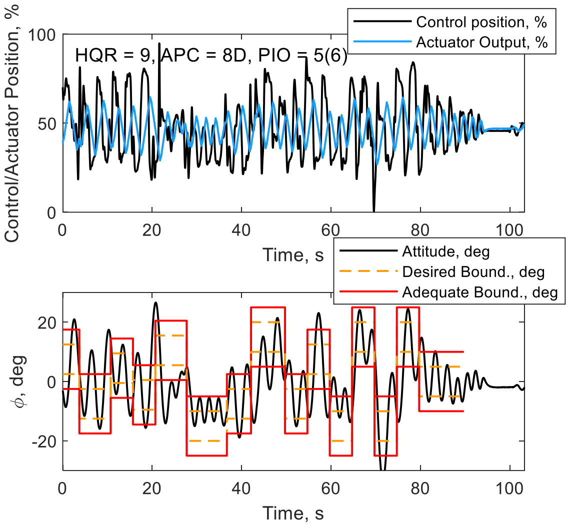

Figure 16: Tracking task, Attitude Command (Good Handling Qualities), RL 17%/s, 400ms time delay, Pilot A

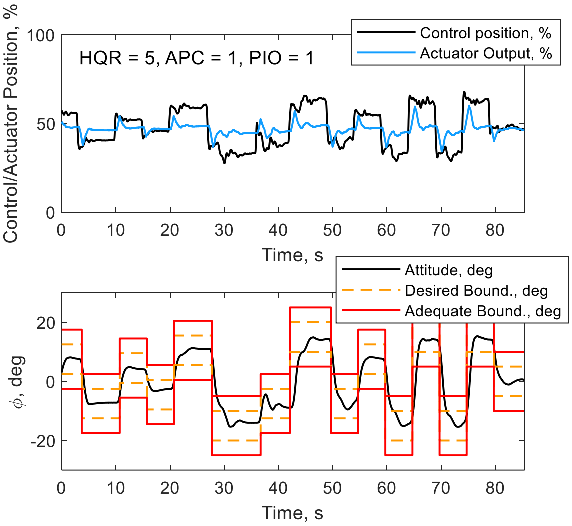

Figure 17: Tracking task, Attitude Command (Good Handling Qualities), RL 17%/s, 400ms time delay, Pilot B

Two of the three events were for cases where the gain bandwidth was lower than the phase bandwidth. Only a small number of cases recorded were in the PIO robust region, and therefore, it is difficult to conclude whether the boundary presented in acceptable or requires modification.

OLOP predictions were compared with APC ratings awarded by pilots during the tests. A full analysis of the OLOP results obtained, with results with respect to MTEs, is contained in [14]. An example of results obtained for the Pirouette task, where many severe Cat. II PIOs were experienced, is shown in Figure 19.

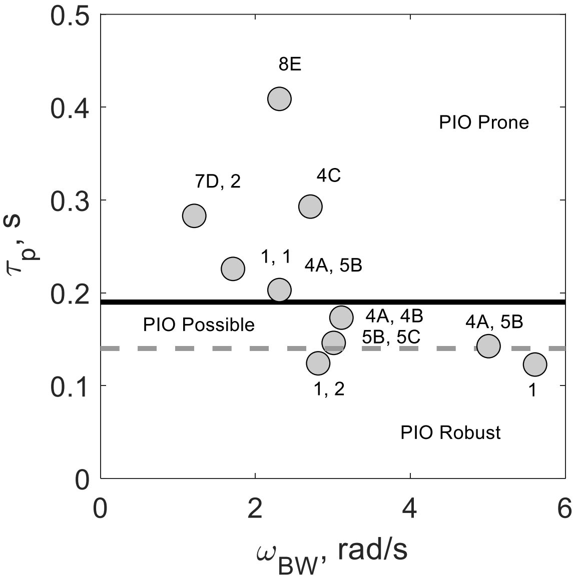

Figure 18: Combination of all no-PIO/PIO from cases with time delays and APC ratings

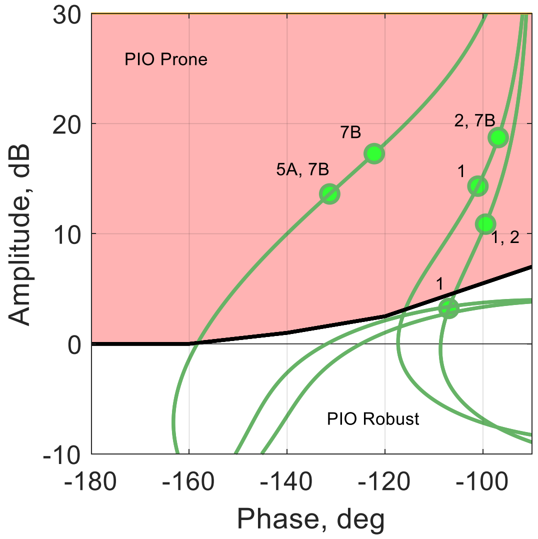

Figure 19: Comparison between Open Loop Onset Point predictions and APC ratings obtained from the Pirouette task performed in the Air Vehicle Simulator

In the OLOP plot, the green markers represent ω_{OLOP} for the various rate limiting values.

Generally, good agreement was found between the modified OLOP results (using Hess pilot model and representative control inputs) and the pilot APC ratings. Particularly for cases with low phase margin at 0dB crossover, the results were consistent with the OLOP boundary. For cases with high phase margin, the boundary appeared too conservative for most cases. This appeared to be task dependent. For example, for cases from the Pirouette task, pilots experienced no perceived PIOs for cases close to the OLOP boundary with a phase margin greater than 60 deg. However, for the Hover task, a number of severe PIOs were experienced for the same configurations.

Based on results obtained, a new proposed boundary for OLOP using the Hess pilot model and appropriate control input magnitude was determined. This is shown in Figure 20. The results show an increased importance of phase margin when determining PIO susceptibility.

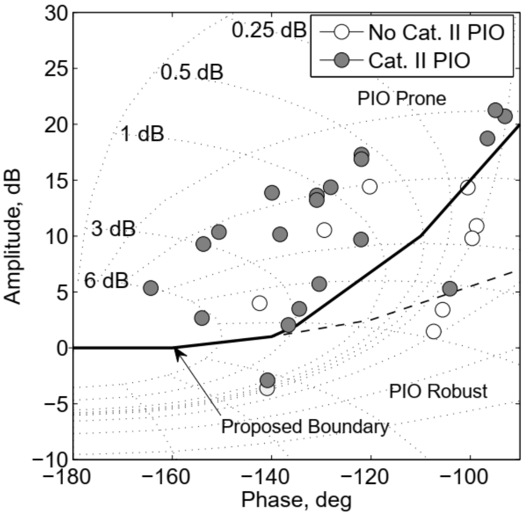

Figure 20: Proposed Open Loop Onset Point boundary based upon results obtained in investigation

As stated a number of results did not conform to the proposed boundary. Notably, three configurations of the ACG case for the longitudinal axis of the Pirouette were found to not lead to Cat. II PIO. This is explained through the baseline HQs of the configuration. The primary axis of the Pirouette manoeuvre is the lateral axis. The off-axis response was found to lead to divergent and large PIOs for some cases due to the poor HQs and required compensation in the axis. For the ACG configuration, the HQs of the axis were good, and therefore the pilot was not required to apply high-frequency compensation. For this reason, the pilots 'gain' was lower for this case and it did not lead to PIOs. Conversely, it is believed that lateral PIOs were found during a hover case due to an increase in pilot gain for this case. The task performance requirements were purposely modified to increase aggression.

One potential drawback of the OLOP method is that it does not account for the mission task or pilot control requirements. In the application used in this investigation, the Hess structural pilot model was used. The Hess model can be tuned to reflect the expected the mission requirements, using the methods discussed in [13,19]. It is therefore believed that this has improved the overall applicability of the criteria to the scenario and vehicle model tested in this investigation.

3.4. Recommendations

As stated, one intended outcome of the campaign in Phase I was to select the cases of interest to be tested in flight tests. Although the campaign at DLR was conducted using different vehicle models and control configurations, experience could be taken from the campaign as follows;

- ADS-33 manoeuvres are suitable to expose PIOs, both in the lateral and longitudinal axes. In particular, the Hover and Pirouette tasks were found to be suitable to expose PIOs in both axes. In addition, the Lateral Reposition manoeuvre was also successful, and could be considered as an additional task. Modifications made were deemed suitable and should be tested in-flight to confirm.
- BPD should be used to assess the incipience to Cat. I (linear type) PIOs. As found in previous research efforts, fixed-wing boundaries appear suitable to determine the PIO susceptibility.
- Modifications to OLOP are considered successful to improve the predictions obtained. Generally, agreement was found between OLOP and piloted simulations. The most severe PIOs resulted from rate limiting. If possible, these cases should be tested in-flight.
- The APC Scale can be used to assess PIOs experienced during flight. The use of the scale was demonstrated during the simulation campaign and should be further tested at NRC facilities.

4. FLIGHT TEST CAMPAIGN

This section details the subsequent flight test campaign conducted at NRC facilities.

The test campaign was conducted using NRC Canada facilities. The goal of this campaign was to utilise techniques and assessment methods developed in the campaign conducted at DLR facilities;

- Use the APC scale for the first time in an in-flight investigation
- Confirm that MTEs tested in simulation are suitable for in-flight investigations
- Test the PAC using data collected in flight.

Tests with rate limits not possible.

4.1. Test Set-up

The NRC Bell 205 (C-FPGV) is an experimental fly-by-wire research facility. The aircraft is used to conduct HQ, control systems and autonomous systems research. A single engine utility helicopter, the basic airframe features a Lycoming T-53-13A turboshaft engine (1,250 shafthorsepower (SHP) take-off rating) and has a maximum gross weight of 9,500 lb. As depicted in Figure 21, the aircraft's main rotor features a 2-bladed teetering design. During its configuration as a research helicopter, the airframe was modified to improve its utility. This included removal of the main rotor stabilizer-bar, fixing the position of the horizontal stabilizer, installation of high skid gear, and the integration of Bell 212 main rotor blades. The fuel system, electrical system, mechanical flight control runs, drive-train, and power-plant remain essentially unmodified.

Figure 21: NRC Bell 205 Airborne Simulator, located at NRC flight test facilities, Ottawa, Canada

The aircraft's variable stability architecture incorporates a single string (simplex) fly-by-wire (FBW) control system, a force-feel inceptor system, and a safety system. The simplex architecture consists of a set of four experimental actuators, a non-redundant flight control computer, aircraft state sensors, and flight management software. The implementation features separate flight critical electro-hydraulic actuators attached to the mechanical control runs actuators attached in parallel to the mechanical control runs and supplied by a dedicated high pressure hydraulic system. When the FBW system is engaged with the evaluation pilot in control of the aircraft, the mechanical control runs are back driven to allow the safety pilot to effectively monitor system performance. Further information on the systems installed in the Bell 205 can be found in [20].

Tests were conducted at NRC facilities in Ottawa, Canada in March 2019. During the flights, visibility was good however the usable cueing environment (UCE) was degraded due to a recent light blanket of snow covering the ADS-33 course. Initially rotor downwash-based snow obscuration caused further degradation of the pilot view. To verify that cues were sufficient to perform MTEs, UCE evaluation was conducted. The degradation from rotor downwash ceased after the course was cleared of the light snow.

4.2. Configurations and Tasks

The NRC Bell 205 control system was configured to allow variations in several parameters to influence PIO tendency. These parameters included different response types (Attitude Command Attitude Hold (AC) and Rate Damped (RD)), rate system bandwidth (as controlled by the rate gain) in both pitch and roll and added system time delay. The evaluation pilot station was configured with standard cyclic, collective, and pedal controls during the trial. In the AC response type configuration, aircraft attitude is proportional to stick input in the lateral and longitudinal axes. In the rate response type configuration, the body axis rate of the aircraft is proportional to inceptor input in lateral and longitudinal axes. Directional and vertical control remained constant throughout the investigation. For vertical control, the collective featured heave damped response. For directional control, the pedals always featured a rate damped response type. For all axes, control characteristics were altered by adjusting gearing and damping.

During the trial, damping in both longitudinal and lateral cyclic axes were modified. This was to alter the aircraft bandwidth. All other axes remained as baseline settings throughout. The goal was to achieve control system damping configurations that resulted in closed loop instabilities and PIOs during the execution of certain pilot tasks. Higher system bandwidth could be achieved through increasing rate damping gains, which subsequently leads to a lower steady state rate and a reduced time to achieve a stabilized steady state rate for a given control input. Low damping was used to drive the control system towards closed loop instability (below structural mode excitation) in the axis selected. Reduction in bandwidth is likely to increase PIO susceptibility, due to the slower response time following disturbance of pilot control.

To provide a range of PIOs during the campaign, four different control systems were used. These were termed;

- Rate Damped baseline (RD)
- Rate Damped Low response type (RDL)
- Rate Damped High response type (RDH)
- Attitude Command Attitude Hold (AC)

The NRC Bell 205 aircraft control bandwidth settings are summarized in Figure 24 for the roll and pitch axes. As during the simulation campaign, BPD was used to assess Cat. I PIO incipience. Using the PIO boundaries from fixed-wing guidance documents, two cases (RDH and AC) were found to be PIO prone due to the high phase delay. In the longitudinal axis, low system bandwidth also suggested that PIO would be possible during completion of MTEs, for the RDL and RD cases.

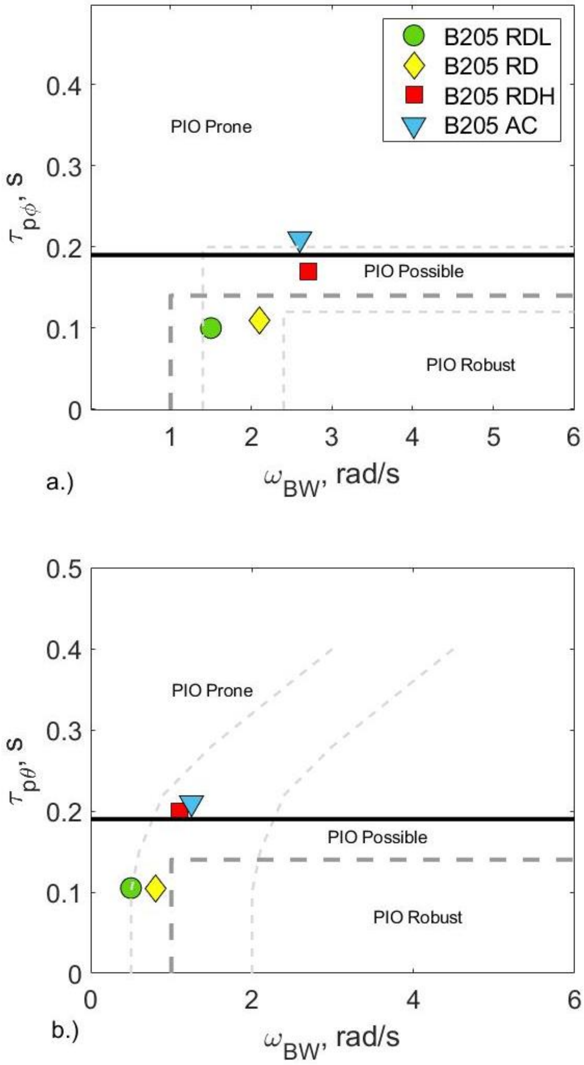

Figure 22: Bandwidth Phase Delay predictions for flight test configurations

Four MTEs were selected from those previously tested in the simulation campaign, namely; Hover, Lateral Reposition, Depart Abort and Pirouette. These were flown using NRC's ADS-33 [3] test course located at in Ottawa, Canada (see Figure 23). As in the simulation campaign, MTE performance standards were defined using external references. An example is shown in Figure 24 during completion of the hover manoeuvre.

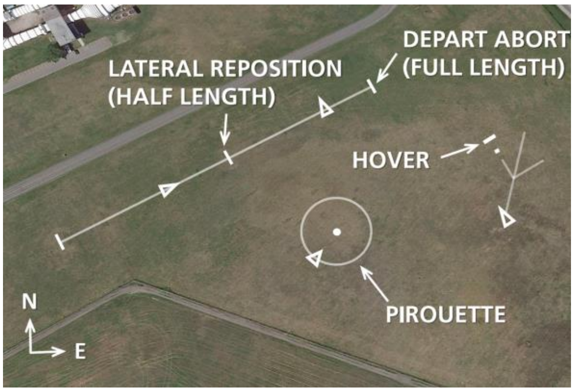

Figure 23: ADS-33 Test Courses located at NRC (Ottawa, Canada)

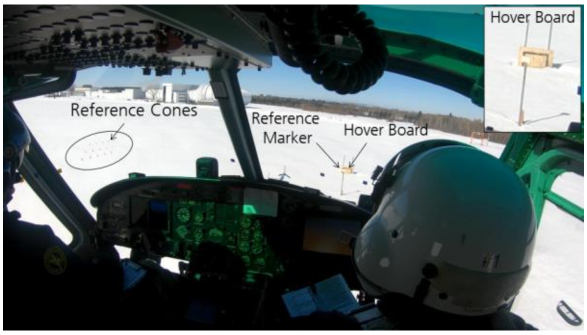

Figure 24: On-board view (NRC Bell 205, Hover task)

4.3. Results

During the campaign, all planned manoeuvres were completed. Due to time constraints, it was not possible to complete configurations for each manoeuvre and therefore, prioritization was performed. In both the simulation campaign and during initial flight test points, the depart abort manoeuvre did not routinely expose PIOs, despite the BPD predictions for the longitudinal axis. Therefore, only one configuration was flown using this task. Furthermore, a number of attempts were made to complete the Lateral Reposition manoeuvre using the AC control system. However, due to the vehicle safety system, this was not possible due to wind conditions of the day, as rate and attitude limits were consistently reached. Both the Pirouette and Hover manoeuvres were completed with all four control configurations.

Table 3 shows the HQRs awarded following completion of each MTE, with respect to the control configuration. As shown, the poorest HQs were found during the completion of the Pirouette. Here, a degradation in HQs was found to be associated with a decrease in system bandwidth.

Table 3: HQRs obtained during flight test campaign

	Pirouette	Hover	Lat. Rep.	Dep. Abort
B205 RD	5; 4	5	4	4
B205 RDL	6	5	4	n/a
B205 RDH	4	4	4	n/a
B205 AC	4	4	n/a	n/a

Table 4: APC Ratings obtained during flight test campaign

	Pirouette	Hover	Lat. Rep.	Dep. Abort
B205 RD	5A; 5D	4A	4A	2
B205 RDL	7C	4B	4B	n/a
B205 RDH	2	1	4A	n/a
B205 AC	1	4B	n/a	n/a

Table 5: PIO Ratings obtained during flight test campaign

	Pirouette	Hover	Lat. Rep.	Dep. Abort
B205 RD	3; 2	2	2	2
B205 RDL	4	2	2	n/a
B205 RDH	2	1	2	n/a
B205 AC	1	2	n/a	n/a

APC and PIO ratings are shown in Table 4 and Table 5 respectively. Characteristics of PIOs experienced during the campaigns varied in terms of severity, duration, and oscillation characteristics. These differences were apparent from subjective pilot ratings awarded. Figure 25 shows the data recorded from two attempted completions of the Pirouette manoeuvre during flight testing. Here, in Case 48, oscillations are apparent. Whereby the PAC results show the contrast between the two cases. For Case 35 (Figure 26), no PIO is detected during the complete run. For Case 48, shown in Figure 27, Severe PIO is detected for almost the complete manoeuvre. This is supported by the APC = 7D rating awarded by the test pilot.

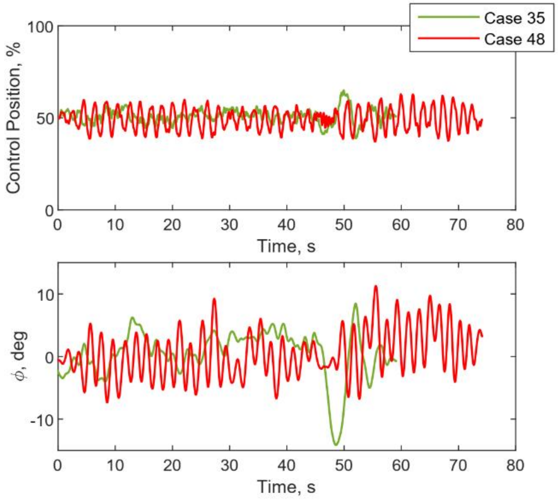

Figure 25: Comparison of Time Responses between two cases of the Pirouette manoeuvre, lateral axis

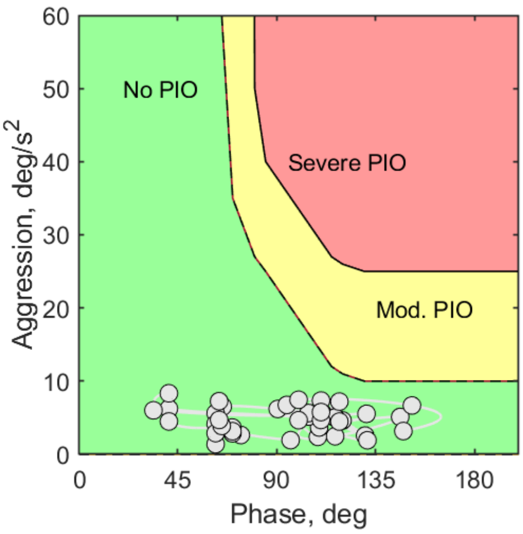

Figure 26: Phase Aggression Criteria detection for Case 35, lateral Axis

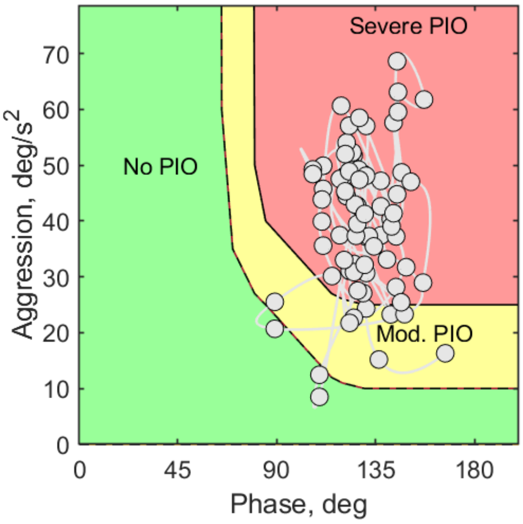

Figure 27: Phase Aggression Criteria detection for Case 48, lateral axis

Table 6 shows a comparison between PAC detections and APC ratings. PAC results from all cases where calculated, both for pitch and roll axis. These results were compared to the APCR, with respect to MTE. The table shows whether the PAC result was found in the roll, pitch, or both axes with non (No.), moderate (Mod.) and severe (Sev.) terms used for reporting results. General agreement was found between PAC and APC ratings. For the Lateral Reposition manoeuvre, PAC did not detect PIO despite the pilot rating of APCR = 4A (in both pitch and roll). Furthermore, for the Depart Abort, the pilot did not recognise a roll PIO (again due to gusting winds), which was detected as moderate oscillations by PAC.

Table 6: Summary of Phase Aggression Criteria PIO detection w.r.t. pilot ratings

PAC	Pirouette	Hover	Dep. Abort	Lat. Rep.
No	2 (roll)	1	n/a	4A (both)
Mod.	5A (roll)	4A (both)	2 (roll)	4A, 4B (roll)
Sev.	7C (roll)	4B (roll)	n/a	n/a

5. DISCUSSION

During both simulation and flight test campaigns, the APC scale was used. The latter were the first tests using the scale for in-flight investigations. Valuable pilot feedback was collected on the applicability and utility of the scale during PIO investigations.

Generally, both pilots agreed that the APC scale solves a number of issues concerning the legacy PIO scale. In this investigation, both scales were used to allow direct comparison. The legacy scale in tabulated form eliminates some of the known problems relating to the use of the subjective decision tree [21]. However, using the tabulated scale, the pilots must award a rating based upon the closest subjective description to the observed PIO. Inevitably, there elements of ambiguity, and not all cases feature all characteristics described in the rating. It is often the case that an observed PIO can fit into the description within 2-3 ratings (of which there are only 6), meaning that the variation can be high across several test pilots, leading to poor data quality and poor reliability. The addition of the decision tree to the legacy scale (not used in this investigation) provides the opposite consequences, whereby the pilots are forced to assign at rating, regardless of the perceived severity. Unlike the Cooper-Harper scale, the pilot does not have any option to subjective award the final rating. The APC scale solves this problem using a decision tree format followed by pilot subjective opinion. The intention is to allow for pilots to use their experience and knowledge to provide assessment, but to reduce the amount of ratings that the pilots may assign. As the questions are based on performance and factual observations, the subjective opinion is minimised, resulting in a decreased variation across several pilots when compared to the legacy rating scale.

The scale also brings focus to the mission task requirements, highlighting the fact that the rating is dependent on these requirements and not a general assessment. Mission task requirements are not prominent in the legacy scale, and the ability of the pilot to adequately perform requirements is not used as a factor in the assessment. The severity of a PIO is directly related to the task that is being flown (and the pilot feedback gain required for the task). The APC rating reflects the ability of the pilot to complete / abandon an MTE and the performance standards achieved. For this reason, it is clear that any assigned APC rating is only applicable when associated with a specific MTE course description and performance standards. This reduces the ambiguity of the assigned rating, providing a clear indication of the situation where PIO incipient conditions are experienced.

Despite favouring the APC scale, pilots did provide suggestions for modifications, particularly concerning the phrasing and wording included. Firstly, pilots were not completely in agreement as to the meaning of the term `adaptation'. They expressed that this should be included with the scale. Adaptation is defined as the degree to which the pilot is required to modify their behaviour and strategy. As contained in [16];

“*If the pilot need not apply any changes to their control or task strategy, this represents negligible adaptation (i.e. they do not need to respond to oscillations). Considerable pilot adaptation refers to the situations where the pilot must consciously act to suppress the oscillations, but may have spare capacity to complete some other tasks.”*

One of the pilots commented that the jump from negligible to considerable pilot adaptation is large. In the Cooper-Harper HQR scale, gradual increments are made using the terms minimal, moderate, considerable, and extensive. The terms should be compared with those used in the APC scale. The pilot questioned whether using the same terminology contained in the HQR scale could provide a benefit, providing standardisation of terms.

Similarly, the pilot also questioned the best way to interpret the additional letter terms. These terms are intended to characterise the oscillations. In particular, what should be pilot state when oscillations have changed due to the pilot adaptation. For example, without adaptation divergent oscillations occur which become sporadic following a change in control strategy. The way in which the rating should be applied is ambiguous. It is the intention that the oscillations experienced prior to adaptation should be provided as feedback. Clearer guidance regarding this point will be used when performing further investigations with the APC scale.

During the investigations, MTEs were taken directly from ADS-33. These were selected as they have well known accepted performance requirements, deemed to reflect those requirements for current operational rotorcraft. The standards are accepted worldwide and used to determine whether vehicles exhibit deficiencies or carefree handling. Some of the ADS-33 task performance requirements also include additional statements regarding undesirable oscillations (i.e. desired performance for the hover manoeuvre).

Whilst the manoeuvres are standardised, the requirements reflect typical expected performance. PIOs often occur following unexpected conditions, often forced by the trigger situation. In order to simulate performance closer to the operational limits of the vehicle, task performance requirements of the hover manoeuvre were modified. These modifications were considered to still reflect operational requirements for utility rotorcraft. Pilots considered that the increase in translation speed had a minor effect on HQ and PIO ratings. PIOs when identified had a convergent nature, often suppressed following a short period. During the completion of the task with increased translational speed, performance must be carefully observed to ensure that pilots to do commence the deceleration early to avoid exposing oscillations.

The decrease in longitudinal and lateral performance tolerances had a greater effect than changing the translation speed. This forced the pilot to increase the feedback gain throughout the hover section and maintenance. As the modification to the task was applied to the maintenance phase, it had a longer term effect and hence produced more sustained PIOs.

Generally, the tracking task was found to be very good to expose PIOs and allowed for simpler analysis of results due to its single axis nature. However, during this task, it was possible for pilots to avoid PIOs by changing the control strategy, whilst maintaining performance requirements. For PIO investigations, this should be avoided, to ensure that all PIO tendencies are uncovered and not masked by pilot strategy. Therefore, the task would be recommended, but with modifications.

As previously stated, the APCRs awarded when using the scale are dependent upon the task performance requirements. When performing tasks as contained in ADS-33 to observe HQ deficiencies, it is acceptable for the pilot to aim to achieve adequate performance tolerances when they are unable to obtain desired performance. This must be demonstrated before the pilot is permitted to fly the task to achieve only adequate performance tolerances. The practice is necessary when awarding HQRs. Regarding PIOs, this has the potential to suppress oscillations and subsequently impacts the APC rating obtained. Therefore, when performing tests to expose PIOs, the following should be observed;

"*Desired and adequate performance standards are required to ensure that the vehicle is flown to known requirements. The pilot should always attempt to achieve desired performance standards, even if these cannot be attained.*"

6. CONCLUSIONS

This paper presents results from a collaborative research effort between the National Research Council Canada Canada (NRC) and the German Aerospace Center (DLR) concerning Pilot-Induced Oscillations (PIOs). Both simulation and flight test campaigns were conducted, sharing knowledge, expertise and large facilities. The following are the conclusions from this work.

A number of mission task elements (MTEs) were successfully employed to expose Aircraft/Rotorcraft Pilot Couplings (A/RPCs) in both the simulation and flight test campaigns. In the simulation campaign, five tasks were used. Versions of four of these tasks were selected for the flight testing. All tasks were found to have some degree of suitability to expose PIOs. Generally, ADS-33 tasks were found suitable in both the lateral and longitudinal axes, in particular the hover and pirouette manoeuvres. Modifications were also applied to the tasks, also considered successful.

The boundaries developed for use with phase aggression criteria (PAC) from simulation campaigns were found to be suitable for in-flight investigations. Results obtained validated boundaries previously developed from simulation campaigns only. This was shown for a range of vehicle control configurations. Correlation was found for both cases where no PIO and PIO were experienced. For this reason, the boundaries are considered suitable for in-flight investigations.

The study described in the paper was limited due to available simulator time and flying hours. In the future, it is recommended that further and more detailed tests should be conducted to modify the ADS-33 MTEs and to improve their suitability to expose RPCs. Furthermore, as previously discussed, pilots commented that modifications to the APC scale could be beneficial. This will be investigated in future research. In this research effort, only simplistic PIO 'triggers' were used (i.e., time delays), as the focus was on tool and technique development. Further research should focus on testing of dynamic PIO 'triggers', such as mode switching and failures. Some recent research efforts have been conducted using simulation and it is planned to continue this research through further in-flight testing.

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APPENDIX

Results from Simulation Campaign at AVES

Results from Simulation Campaign

DA = Depart Abort
H = Hover
LR = Lateral Reposition
P = Pirouette
RT = Roll Tracking

Table 7: Simulator results with time delays applied in the longitudinal axis

Task	Command	Time Delay	APC	PIOR
DA	RC	0ms	1,2	1,2
DA	RC	200ms	1,1	1,1
DA	RC	400ms	7D,2	4,2

Table 8: Simulator results with time delays applied in the lateral axis

Task	**Command**	**Time Delay**	**APC**	**PIOR**
P	RC	0ms	1	1
P	ACP	0ms	5C, 5B	3,4
P	ACP	400ms	8E	6
RT	ACG	0ms	1	2
RT	ACG	200ms	4A, 4B	2,2
RT	ACG	400ms	4A, 5B	2,3
RT	ACP	0ms	4A, 5B	2,3
LR	RC	0ms	4	2
LR	ACP	400ms	4C	3

Table 9: Simulator results with rate limits applied in the longitudinal axis

Task	**Command**	**RL (%/s)**	**APC**	**PIOR**
DA	RC	N/A	1,2	1,2
DA	RC	35	4A, 4C	2,2
DA	RC	17	4B	2
P	RC	N	1	1
P	RC	17	5D	6
P	RC	10	4A	2
P	ACP	35	7B	4
P	ACP	17	5A, 7B	2,4

Table 10: Simulator results with rate limits applied in the lateral axis

Task	**Command**	**RL (%/s)**	**APC**	**PIOR**
P	RC	N/A	1	1
P	RC	35	1	1
P	RC	17	1	1
P	ACP	17	4C	4
RT	RC	17	2,1	2,1
RT	RC	35	1	1
RT	ACG	35	1	1
RT	ACG	17	2, 7B	2,4
RT	ACP	35	7B	4
RT	ACP	17	5A, 7B	2,4
LR	RC	N/A	4	2
LR	RC	35	2	2
LR	RC	17	2	2
LR	ACP	35	5C	3
LR	ACP	17	8E	5

Table 11: Simulator results with rate limits applied in the lateral and longitudinal axes

Task	**Comm.**	**RL (%/s)**	**APC**	**PIOR**
P	ACG	N/A	1	1
P	ACG	35	1,1,1	1,1,1
P	ACG	17	1,1	1,1
P	ACG	10	2	2
H	RC	N/A	4A	2
H	RC	35	5B, 5C	3, 4
H	RC	17	5C, 5C, 8E	4, 4, 5
H	ACP	35	4C, 5B, 7D	2, 3, 4
H	ACP	17	4C,4C,5C 7D,9E	2,2,4,4,6