PAPER #123

EXPOSING ROTORCRAFT PILOT COUPLINGS USING FLIGHT SIMULATION

Michael Jones, Michael Jump, and Linghai Lu,
{michael.jones,mjump1,linghai}@liverpool.ac.uk, University of Liverpool. (UK)

Deniz Yilmaz, and Marilena Pavel,
{d.yilmaz,m.d.pavel}@tudelft.nl, Delft University of Technology. (NL)

Pierangelo Masarati, Giuseppe Quaranta, and Vincenzo Muscarello,
{masarati,quaranta,muscarello}@aero.polimi.it, Politecnico di Milano. (IT)

Abstract

Unmasking Aircraft and Rotorcraft Pilot Couplings (A/RPC) prior to vehicle entry into service has been a long standing challenge in the aerospace industry. A/RPCs, often only exposed through unpredictable or very specific circumstances have arisen throughout the history of manned powered flight, and have required short-term 'fixes' to ensure system safety. One of the reasons for this occurrence is the lack of detailed practice regarding the prediction and detection of RPCs prior to full-scale testing. Often in simulation, A/RPCs are only investigated once problems have been experienced during other qualification activities. This is a particular issue for the rotorcraft community, where system sophistication is 'catching up' with their fixed-wing counterparts. This paper shares results from real-time simulation campaigns conducted during the European Collaborative ARISTOTEL project. Results are included from tests, conducted in full motion simulators, specifically designed to unmask Rigid Body and Aeroelastic RPC tendencies. Results from this paper act as guidelines for exposing RPCs in real-time simulation campaigns. This includes the introduction of novel test procedures and analysis methods.

1 INTRODUCTION

This paper reports upon the activities undertaken as part of the European Commission's 7th Framework Programme project ARISTOTEL (`http://www.aristotel.progressima.eu/`) [1–4] with a particular focus on the real-time simulation elements of the research.

With the demands and costs associated with the aviation industry driving end-users increasingly towards simulation for both training and research activities, the use of real-time flight simulation is becoming more important than ever before. With the potentially favourable costs, increases in safety, and the ability to 'manage' the environment, simulation can offer considerable benefits over full-scale flight testing. This is particularly true when the activity involves deliberate attempts to trigger potentially catastrophic events, such as adverse Aircraft/Rotorcraft Pilot Couplings (A/RPC). Research into this phenomenon has seen renewed interest over the last few years over concerns that both the severity and frequency of such 'events' will increase [1–4]. The potentially aggressive and violent nature of the resultant vehicle response would be a major flight safety risk. Therefore, to routinely expose and study these events, in a notionally safer environment, the preferred option must be to use simulation. Of course, a 'simulated' environment is not perfect and the deficiencies in the synthetic environment must always be taken into account.

The ARISTOTEL project aims to provide tools, techniques, and guidelines to allow the prevention, detection, and alleviation of adverse aircraft/rotorcraft pilot couplings (A/RPC). Within the project, all of the experimental research to date has been conducted using simulation, through either 'real-time' or 'offline' analysis. All pilot-in-the-loop flights have been conducted using full-motion flight simulators. The focus on simulation has allowed the project scope to investigate some of the current deficiencies regarding simulation prediction and detection of RPCs via testing.

In order to provide an assessment of the potential of any vehicle model to exhibit RPC tendencies, it is considered essential, at some stage in the process, to use piloted simulation. Whereas for a number of other research areas, simulation is preferred due to its availability and cost, when dealing with RPCs, it is the safety benefit which is paramount. It would be difficult to obtain clearance to conduct a full-scale flight tests with conditions predicted to cause instability and strong RPCs. The main drawback of using simulation for RPC studies, however, is the absence of current and relevant guidelines. Whilst some form of standards exist for training devices (for example standards outlined in Ref. [5]), they do not exist for research simulators, including those used for RPC research (this is true also for the fixed-wing community). It is intuitive that piloted simulation conducted at desktop level and piloted simulation conducted in a Level D certified simulator will potentially result in different outcomes for a variety of test cases. For the ARISTOTEL consortium, it is also likely that the two would provide very different results with regards to the assessment of the RPC potential for a particular pilot-vehicle combination. Therefore, it is of interest to ascertain the sensitivity of the results obtained using two different simulation devices, all other things being equal (or as equal as it is possible to make them).

The paper proceeds as follows. First, the results from the project's Rigid Body (RB) investigations are discussed. The section presents key findings and results from two test campaigns. Second, Aeroelastic (ASE) investigations are discussed, and some key results are presented. Finally, conclusions from all of the investigations are presented.

2 RIGID BODY INVESTIGATIONS

2.1 Overview

In ARISTOTEL, Rigid Body (RB) investigations focus on the response of the active pilot, coupled with low frequency vehicle dynamics (typically less than 1Hz). Oscillatory events in this frequency range are termed Pilot-Induced Oscillations (PIO), recognising the necessary presence of the pilot within the control loop. PIOs refer to the situation where the pilot no longer drives the oscillations, but is driven by the oscillations. Here, there is a mismatch between pilot and vehicle dynamics, causing system instability. For the simulation test campaigns described within this paper, both the University of Liverpool (UoL) and the Technical University of Delft (TUD) created simulation models of the MBB Bo105, using data obtained from GARTEUR Helicopter Action Group 16 (GARTEUR-AG-16, [6]). Furthermore, the low frequency response characteristics were verified through a comparison with flight test data, and results from previous modelling efforts [7]. A full description of the modelling and validation exercise is contained within Ref. [8].

Rigid Body models were flown real-time using two full-motion simulators; SIMONA (SRS, Fig.1(a)) and HELIFLIGHT-R (HFR, Fig.1(b)). Full descriptions of these facilities are contained within Ref. [9] and Ref. [10] respectively. Due to the hardware limitations, a number of differences in the cueing environment exist between the simulators. These differences are discussed in detail in Ref. [11].

Within the ARISTOTEL project, two Rigid Body Test Campaigns (RBTC) were conducted. The 1st RBTC was primarily used to continue investigations initiated in GARTEUR AG-16. Recommendations outlined in Ref. [6] stipulated the requirement for further results to provide justification for rotorcraft PIO susceptibility boundaries for prediction criteria. Therefore, in this campaign, predictions were made using candidate criteria, and piloted assessment was used to determine the efficacy of these predictions. A full description of this effort is contained within Ref. [12]. The 1st RBTC was also used to assess improvements with regards to the trial process, that could be implemented for the planned 2nd RBTC. Furthermore, results from the 1st RBTC were used to define the research questions for the 2nd RBTC. The 2nd RBTC focussed on the development of tasks and manoeuvres to expose RPC tendencies. The sensitivity of the vehicle model to RPC incipience was observed through changes in task performance.

For both RBTCs, a number of current or former military test pilots were used. Four pilots participated in the 1st RBTC (Pilots A-D). All pilots completed tests in both SRS and HFR. In the 2nd RBTC, a total of 5 pilots participated, three of whom completed tests in both SRS and HFR (A,C-D). Pilots E and F completed tests in only HFR and SRS respectively. Pilot B did not participate in the 2nd RBTC.

During both campaigns, RPC incipience was judged through pilot subjective assessment. In both test campaigns, vehicle handling qualities and task difficulty were measured using the Cooper-Harper Handling Qualities Rating (HQR) Scale [13]. Furthermore, in the 1st RBTC, pilot workload was measured using the Bedford Workload Rating Scale [14]. In the 1st RBTC, RPC tendencies were assessed using the Pilot Induced Oscillations Susceptibility scale, shown in Fig. 2. In the 2nd campaign, due to reasons which will be discussed in the subsequent sections, a novel PIO scale was introduced. This is shown in Fig. 3. In this paper, ratings awarded using the traditional and new PIO ratings scales are termed PIOR and N-PIOR respectively.

(a) SIMONA full-motion simulator

(b) HELFLIGHT-R full-motion simulator.

Figure 1: Simulation devices used in RBTC.

2.2 Lessons Learned from Rigid Body Test Campaign 1

For the sake of brevity, the focus of the paper is on the results of the second campaign. However, the lessons learned from the first campaign are also described below.

1) Suitability of Tasks to Expose RPCs

The primary objective of the 1st RBTC was to assess the suitability of ADS-33 type tasks to expose RPC tendencies in the vehicle model. A number of candidate manoeuvres were selected, shown in Table 1. These were selected to exercise the longitudinal,

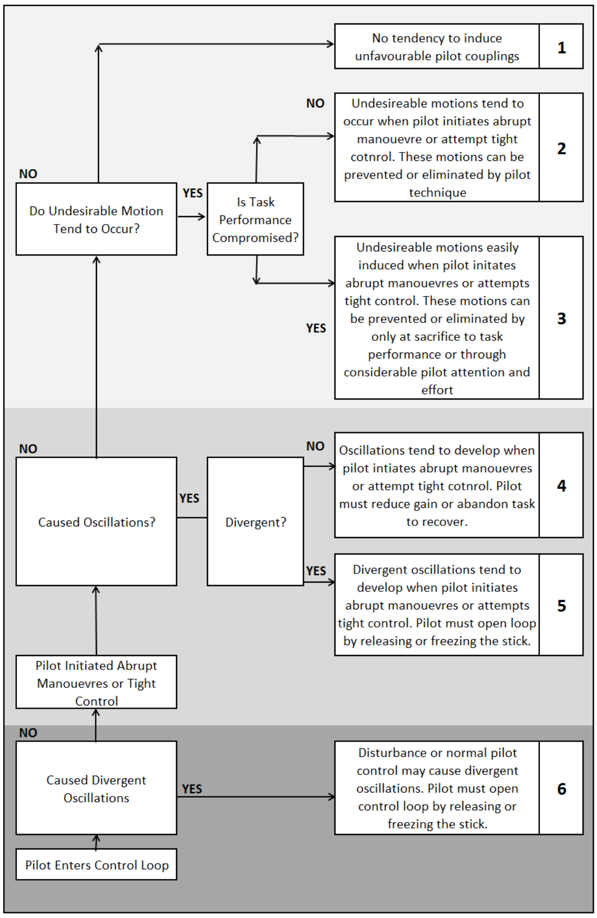


Figure 2: The traditional PIO scale used in the 1st RBTC.

lateral, and heave axes of a typical helicopter. Furthermore, many were used in the AG-16 RB simulation campaign [15]. Table 1 displays the key findings regarding the suitability of the tasks in relation to unmasking RPC susceptibility. Advantages, disadvantages, and recommendations for each task are also shown. From these findings, it was evident that there were three primary reasons for poor task suitability.

First, the task bandwidth/performance requirements were not suitable to expose RPCs. This was apparent for two of the lateral tasks, the Slalom and Roll Tracking. The Slalom is defined in ADS-33, and is commonly used to assess turn coordination, objectionable inter-axis coupling, and the ability to manoeuvre aggressively in forward flight. The difficulty of the manoeuvre may be engineered through placement of test course markers and through the forward flight speed of the rotorcraft (both influencing the task bandwidth). The manoeuvre was used within the AG-

16 project [15]. However, in the 1st RBTC, it was apparent that the task bandwidth was insufficient to expose adverse couplings. When used to expose linear type oscillations, the pilot stated that all they had to do was focus on timing. Applying slow and constant lead, the pilot was able to complete the manoeuvre with very limited control activity, and within performance standards, with 400ms of additional time delay in the control loop. This is shown in Fig.4 for three different cases completed in SRS. Predictions show that this time delay should cause significant difficulty. Whilst it is seen that the task, for some pilots may expose significant PIO events, the variability for which one can attempt the manoeuvre makes it a poor choice to expose RPCs. Furthermore, increasing task bandwidth would lead to inadequate control margin for control. One part of the slalom that showed potential to unmask RPCs was the final stabilisation segment. Here, at the end of the manoeuvre, the pilot must translate to the centre of the runway and maintain track along the centre markers. Demonstrations of the capability to cause RPC in this stage of task completion led to the use of the Roll Step (RS) manoeuvre, outlined in Ref. [16], for future tests.

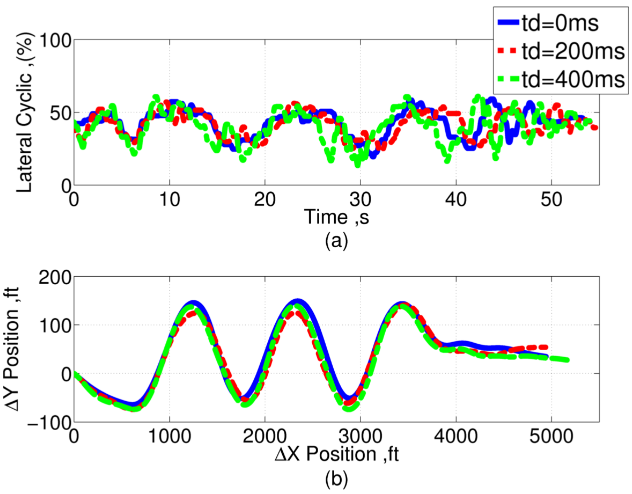


Figure 4: Pilot lateral cyclic input (a) and slalom course ground trajectories (b) for 0ms, 200ms, and 400ms of applied time delay.

The Roll Tracking task, as defined in Ref. [15] was considered to not be suitable as the physical capabilities of the vehicle did not allow the task to be completed. The required roll rates meant that the pilot could not complete the task. Furthermore, the task set-up did not allow for the assessment of adequate and desired task performance. Therefore, it was not possible to provide clear subjective ratings.

Second, simulation fidelity was not adequate for task completion, and became the focus of pilot attention. The available visual references were a significant issue for both the Sidestep and Accel-Decel manoeuvres, particularly in SRS. A comparison of simulator FoV is shown in Fig. 5. Due to the limited Field-of-View (FoV), when completing the deceleration phase of the Accel-Decel, in both simulators, pilots lost all visual references. In the real-aircraft, although visual references would be sparse, the pilot would have some available. When visual references were lost in the simulation, pilots were effectively no longer flying the task, as they were not able to determine whether or not that were within desired or adequate tolerances. The visual FoV in SRS was insufficient for the completion of the Sidestep manoeuvre, as the target point on the course could not be seen whilst completing the manoeuvre. This made the task unrealistic, and almost impossible to complete.

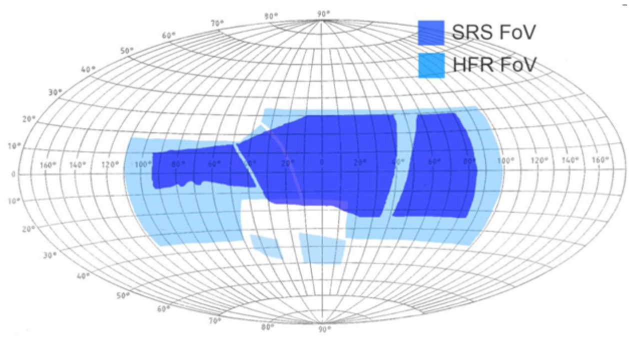


Figure 5: Comparison of HFR and SRS FoV. [17]

Third, on some occasions, the task performance requirements were too stringent for the adequate assessment of RPC tendencies. For tasks where this occurred, pilot workload was focused on manoeuvre completion, and not on evaluation of RPC tendencies. Therefore, upon completion of each manoeuvre, they found it difficult to provide a subjective assessment. This was particularly the case for the Vertical Manoeuvre, where high cross-couplings within the vehicle model causes high off-axis pilot control. Here, highly scattered subjective ratings were provided.

2) Subjectivity of the Pilot-Induced Oscillations Ratings Scale

In the 1st RBTC, the primary assessment of RPC potential was made through the use of pilot subjective opinion. This is the traditional method for assessing RPC tendencies. The assessment was conducted using the Cooper-Harper Handling Qualities Ratings Scale (Ref. [13]), and the traditional combined

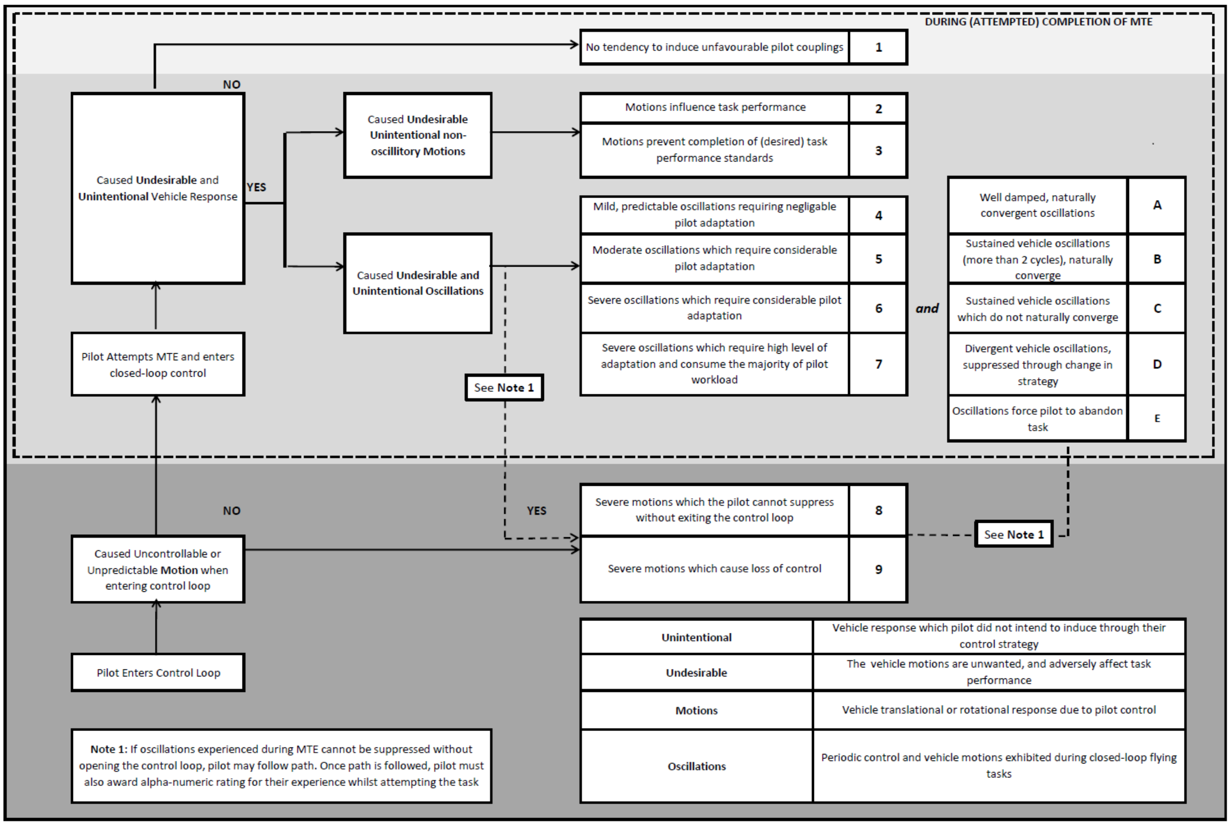


Figure 3: The New PIO scale used in the 2nd RBTC.

Pilot-Induced Oscillations Ratings Scale (PIOR). The latter of these scales is shown in Figure 2.

During the campaign, many problems were experienced with the use of this scale, some of which have been previously highlighted in Ref. [18]. From the investigations that were undertaken as part of ARISTOTEL, some of the main problems were as follows.

The first major drawback found was the influence of a lack of the available subjectivity in the scale. Unlike the HQR scale, the PIOR scale decision tree offers the pilot very little subjectivity. Pilots are trained to apply subjectivity, but are almost forced not too. If the pilot follows the decision tree based on a simple appraisal of what happened during the test, they are forced towards a numerical and descriptive rating. On many occasions, the description was found to be inconsistent with the experience during the evaluation run. As each strand of the decision tree leads to a different rating, any deviation from the given rating invalidates the decision tree. The HQR scale (Ref. [13]) for example offers the pilot the chance to apply subjectivity after the use of the decision tree. This gives results that are not simply determined from the answers to polar questions.

The second, related problem, is the apparent mismatch between the decision tree and the descriptive terms. Originally, only the tree was presented by the Calspan corporation. However, in order to improve the interpretation of the results, descriptions were 'fitted' to numerical ratings. In some studies, only the descriptive terms are used. This creates inconsistency between investigations conducted using the PIOR scale. One of the main issues that was found during the 1st RBTC campaign was the mismatch between the tree and the descriptions. Pilots often felt that the tree took them to the 'wrong' description; a common occurrence was arriving at PIOR 4, whilst wishing to use the description of PIOR 3. A major issue is that the end result from the application on the scale is often the assessment of a single number. The meaning of that number is very dependent on whether the descriptive terms have been used. Often PIOR $>=4$ is used to denote observed PIOs. However, there is nothing in the scale to say that 'undesirable motions' cannot be classed as PIOs. What if the pilot does not need to reduce gain or abandon task to recover? What if he must only change strategy to counteract PIO? Finally, the scale gives little justification for the meaning of the numbers. Furthermore, the significance placed upon convergent/divergent oscillations, one of the most challenging elements to assess, makes the analysis of results very challenging. If the pilot feels that convergent oscillations have occurred after entering tight control, no matter the severity, they must award PIOR 4. It is possible that these oscillations have caused a loss of control. This makes it very important to compliment PIORs with HQRs.

Finally, the need for clearer descriptions and definitions within the scale was clear during the investigations. Pilots had conflicting views on what constituted oscillations, and motions. Overall, it was determined that a new assessment method was required for the second campaign.

3) Simulation fidelity and its impact

As stated in the preceding Section, the simulators used in this investigation have different hardware and software capabilities, which impact the relative overall simulation fidelity. For RPC investigations, there are no standards which require objective assessment of simulation device fidelity. However, the set-up of the device is known to significantly affect results obtained from any investigation. A complete sensitivity study into the effects of the cueing environment was beyond the scope of the 1st RBTC. However, an attempt to quantify the overall fidelity difference between the simulators was made, using subjective measures, namely the Usable Cueing Environment (UCE, [19]) and the Motion Cueing Ratings Scale (MCR, [20]). The UCE assessment process is described within Ref. [19], and is used to assess the visual cues available to the pilot through their perception of attitude and translational cueing. In the 1st RBTC, all pilots awarded UCE's for the 'baseline' Bo105 configuration. Results are shown in Fig. 6. As shown, due to the larger FoV, HFR consistently exhibited better Visual Cueing Ratings (VCRs) than SRS. The result was that the pilots found tasks easier to complete in HFR, finding it less challenging to maintain task performance requirements (which are obtained from the UCE). Translational cues were a major factor in the SRS UCE ratings, their absence contributing to significant pilot workload to allow task completion. This ultimately impacted the spare capacity that the pilot had to assess the RPC tendencies, increasing ratings scatter and decreasing pilot confidence. The two tasks that suffered the least from the lack of visual cueing were the Precision Hover (PH) and the Roll Step (RS) manoeuvres. Both received Level 1 UCE ratings for both simulators, and pilots were able to adequately assess a) whether they were meeting task performance requirements and b) whether RPCs were impacting their ability to perform the task. It is suggested that when conducting RPC studies, UCEs are collected and should be verified so that the cueing is sufficient for task completion. This should allow the pilot to adequately assess RPC incipience, and significantly reduce the ratings scatter.

2.3 Rigid Body Test Campaign 2

The 2nd Rigid Body Test Campaign (RBTC) was conducted between March-April 2013, both using SRS and HFR.

Rigid Body Prediction

The experimental configurations used for both RBTCs were informed through the use of prediction techniques, specifically used to ascertain rotorcraft tendency to low frequency PIO. These tools used were originally developed for the analysis of fixed-wing PIO tendencies, and later applied to rotorcraft problems. In order to determine model incipience to PIO, first full-nonlinear models were linearised to determine RB state-space equations. Incipience to linear type PIOs, typically caused by vehicle time delays, was determined through the application of bandwidth-phase delay (BPD) criterion. BPD is contained in both ADS-33 [19] and MIL-STD-1797-C (for fixed-wing aircraft, Ref. [21]). The criteria is used primarily in ADS-33 to determine predicted HQ Levels, using defined mission-task and axis specific boundaries. The BPD boundaries contained in Ref. [21] directly relate to PIO incipience. The suitability of the fixed-wing boundaries for rotorcraft predictions has previously been shown in Refs. [6,22]. The susceptibility to quasi-linear type PIOs, those typically caused by control path rate or saturation limits, was determined through the application of Open-Loop Onset Point criteria (OLOP). The method was developed by DLR using describing function techniques and stability regions of the Nichols chart [23]. The OLOP is defined as the frequency response value of the open-loop system at the closed-loop onset frequency. The closed-loop system describing function is characterised by a 'jump' phenomenon after rate limiting offset. OLOP was used to determine the PIO susceptibility to rate limiting elements (RLE) in the forward control path. These were modelled at the output of linear approximations. A full description of the application of the criteria, and results obtained is contained within Refs. [12,24]

Table 1: Appraisal of task suitability during tests conducted in the ARISTOTEL project.

Manoeuvre	Proposed RPC Uses	Use in Handling Qualities Research	Positives	Negatives	Considerations
Precision Hover (PH)	Incipience in all axes, predominantly roll and pitch, hover	Check ability to maintain precise position, heading and altitude following transition from translating flight	•Clear Increase in PIO susceptibility with increasing time delay (roll and pitch) •Multi-axis task appears suitable for exposure of PIOs in all axes (Pitch, Roll, Yaw, Heave) •Suitable for assessment of cross-couplings	•Lack of high gain pilot control demand after hover board capture •Requires large visual FoV to adequately capture ground references	•Alteration of hover board size •Additional disturbances to force pilots to achieve tighter control during the stabilization element
Vertical Manoeuvre (VM)	Incipience in heave and yaw axes, hover	Assess heave axis controllability, adequate damping and undesirable couplings	•Reduction in handling qualities and increase in PIO susceptibility with increasing time delay	•Highly scattered PIO ratings, due to significant cross-coupled vehicle model •Task aggressiveness showed limited differences in subjective ratings	•Manouevre suitability in question when off-axis stabilization is required •Auto-compensation for cross couplings to achieve a higher HQ rotorcraft model
Slalom (S)	Incipience in the roll axis, forward flight	Check for the ability to manoeuvre in forward flight and objectionable cross-couplings		•Highly predictable, pilots were able to complete with open-loop control even with high triggering configurations •Additional side walls did not improve the pilot compensation effort	Additional disturbance to force pilots to achieve tighter control •Variable distance between slalom poles could reduce predictable nature of task
Sidestep (SS)	Incipience in the roll axis, hover and low speed	Lateral direction handling qualities for aggressive manoeuvring and undesirable cross-couplings	•High control activity in lateral axis •Clear tendencies for PIO	•Requires large horizontal field of view to complete manoeuvre successfully	•Manoeuvre suitability in question when limited horizontal FoV
Roll Step (RS)	Incipience in the roll axis, forward flight	N/A	•High control activity on lateral axis •Increase of HQR with increasing time delay	•Difference in course specifications at different facilities •High aggression requires large simulator motion travel (or low motion gains) •Scattered PIO ratings	•Standardise roll step course •Adjusted motion filters to ensure preservation of motion travel margins
Roll Tracking (RT)	Incipience in the roll axis, hover and forward flight	N/A		•Unnatural single axis no motion task with high bank angle commands •Hard for pilots to distinguish commanded roll and the vehicle response •Limited time for pilots to achieve commanded bank with the vehicle model	•Redesign of the task commands with vehicle capabilities •Visual design desired and adequate boundaries
Accel/Decel (AD)	Incipience in the pitch axis, hover and low speed	Longitudinal handling qualities for aggressive manoeuvres and undesirable couplings	•'Explosive' PIOs obtained during the stabilization element of the task with time delays and rate limits	•Requires large vertical FoV •Difficult task to achieve, particularly for rotorcraft with large cross couplings	•Provide additional cueing to pilots •Manoeuvre suitability in question when off-axis stabilisation is required
Pitch Tracking (PT)	Incipience in the pitch axis, hover and forward flight	N/A	•Largely successful at exposing RPCs due to rate limiting elements •Easy to impliment and easy for the pilot to understand performance requirements	•Boundary width allowed pilot to operate open-loop with certain control strategies •Has the potential to lose 'realism' from rotorcraft tasks •Requires Head-up display	•Either apply external forcing function on aircraft/boundaries or decrease the boundary width to force pilot control gain

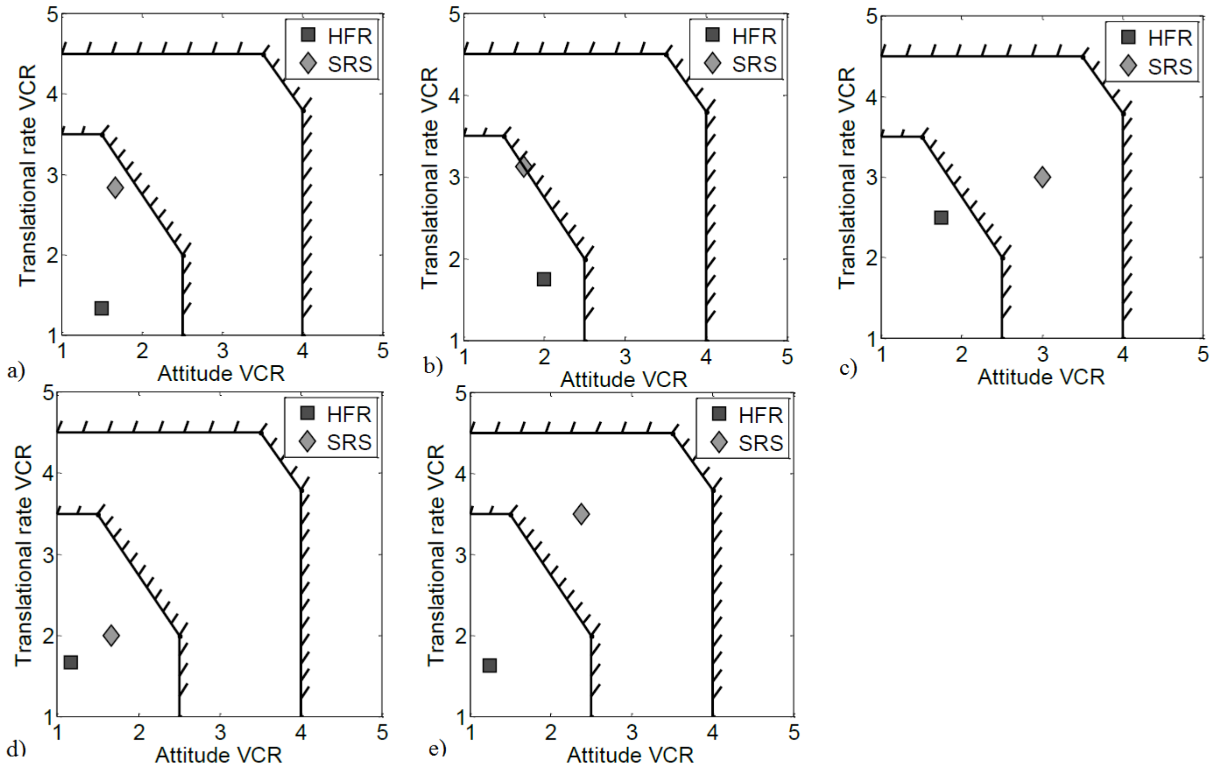


Figure 6: Useble Cueing Environment ratings (a = PH, b = VM, c = AD, d = RS, e = SS).

During the 2nd Rigid Body Test Campaign, the Bo105 simulation models were used for both low speed and forward flight tasks. Model PIO susceptibility was engineered through the use of both transport delays and system RLE. Transport delays were applied at the pilot input, whilst RLE were applied at the swashplate output. The configurations were selected using the prediction criteria described above. For both low speed and forward flight configurations, delays and rate limits that produced 'boundary cases' were applied to the vehicle. The test cases flown in the investigation are shown in Table 2. Case 1 represents the 'baseline' case, where no PIO triggers were added. This model was predicted to be robust to PIO, with high system bandwidth and no RLE. Configurations 2 and 5 were selected as to be prone to linear PIO in the roll axis. This was triggered through the application of time delays in the control path. Configuration 3 was selected to be prone to quasi-linear PIO only, in both the lateral and longitudinal axes. Finally, Cases 4 and 6 were selected to give a combination of triggers, so these cases were predicted to be prone to both linear and quasi-linear PIOs.

Table 2: Configurations tested during the 2nd RBTC.

CONF.	Long. Delay	Long. Rate Lim.	Lat. Delay	Lat. Rate Lim
1	0	∞	0	∞
2	0	∞	250	∞
3	0	5	0	2.5
4	180	5	250	2.5
5	0	∞	220	∞
6	0	∞	220	2.5

Task Performance Requirements

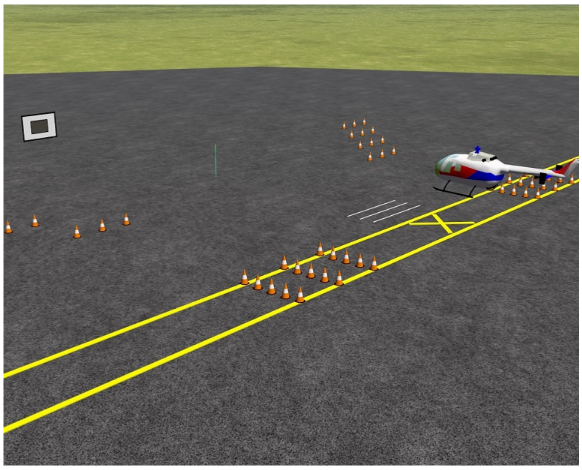
Based on results from the 1st RBTC, and conclusions shown in Table 1, only two tasks were selected for use in the 2nd RBTC; the Precision Hover (PH) and Roll Step (RS). However, modifications to the tasks were required, to improve their suitability to unmask RPCs.

The PH manoeuvre, contained within ADS-33 [19], is a multi-axis re-position stabilization task to assess low speed performance. The task assesses both the ability of the aircraft to transition from translating flight to hover, and the ability to maintain precise position. Task performance is driven by a series of visual elements, positioned within the environment. The primary height and lateral cueing is given by the 'hover board'.

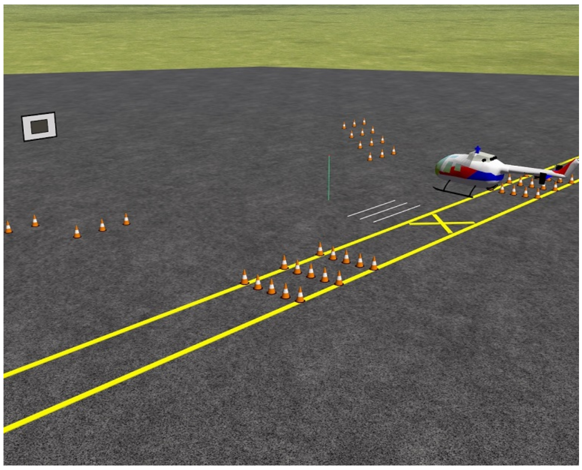
During the 1st RBTC, during completion of the PH manoeuvre, experimental cases were completed where pilots were asked to increase their aggression, in order to observe differences in RPC potential. The difference in RPC potential through a reduction in hover board size was observed, and offered an interesting outcome. Forcing the pilots into tighter control caused them to expose more deficiencies in the vehicle, and increases their incipience to RPC. Moreover, the results from simulation were found to better reflect predictions.

The manoeuvre task performance was engineered by making changes to the reference pole location. Pilots were required to maintain a stabilised hover whilst keeping the pole reference position within the hover board from their point of view. It is usual for the pole to be placed midway between the hover board and the reference hover location. ADS-33 [19] recommends a distance of 150ft between the aircraft and hover board, with the pole located 75ft from the aircraft. If the reference pole is moved closer to the aircraft, it decreases the tolerances for completion of the task. In the investigation, 3 pole locations were used; 75ft, 40ft, and 20ft from the aircraft. The distance between the aircraft and the hover board was kept constant at 150ft. This causes changes to the lateral, longitudinal, and height tolerances, given directly by the cueing environment. For example, with the reference pole at 20ft, tolerances are reduced by a factor of 5. However, heading tolerances directly given by the cueing environment, along with longitudinal track position, remain unchanged. Figure 10 shows the pole at the central location (75ft) and at the closest (20ft) location. Excluding changes in the reference pole location, the course was set-up to replicate performance standards for Scout/Attack and Cargo/Utility rotorcraft (as outlined in Ref. [19]).

As previously stated, HQRs were used to judge both the vehicle handling qualities (linked to RPC) and the task performance. With changes in HQR, one can observe the relative changes in task difficulty through changes in the tolerances. Table 3 displays Handling Qualities Ratings (HQRs) for the baseline vehicle model (PIO robust). Results are shown for both tests completed in HFR and SRS. Next to each numerical rating, subscripts denote the number of times the rating was awarded. For HFR results, predominantly Level 1 HQRs were awarded for the 75ft pole location, the task as defined in ADS-33. However, in SRS, due



(a) External view of standard ADS-33 Precision Hover course setup



(b) External view of modified Precision Hover course setup

Figure 7: Examples of Precision Hover course layout used during investigation.

to the poorer cueing environment and lack of ground references, the task was found to have predominantly Level 2 HQRs. HQRs were not shown to be sensitive to pole location within SRS. This is due to the initial difficulty in task performance. However, in HFR, the position of the pole location changed ratings from predominantly Level 1 to Level 2 HQRs.

Appendix A contains tables of all N-PIORs awarded by pilots completing the PH manoeuvre. These are separated with respect to pilots, vehicle configuration, and pole location. Overall, the cases shown seem consistent between both simulators for Configurations 1,3, and 7. For Configuration 1 (the baseline, PIO robust case), there was a greater tendency for pilots to award N-PIOR > 3 in SRS.

Configuration 4 shows significant differences bet-

Table 3: HQRs awarded during completion of PH.

Pilot	HFR Pole Location (ft)			SRS Pole Location (ft)		
	20	40	75	20	40	75
A	4, 5	4	3, 2	$5_{(3)}$	6	6
C	5	$5_{(2)}$	3	$5_{(2)}$ 7	4, 5	$4_{(2)}$
D	7	5	3	5, 6, $7_{(4)}$	$6_{(2)}$, $7_{(5)}$	$5_{(2)}$, $6_{(2)}$, $7_{(2)}$
E	4	5	$4_{(3)}$	-	-	-

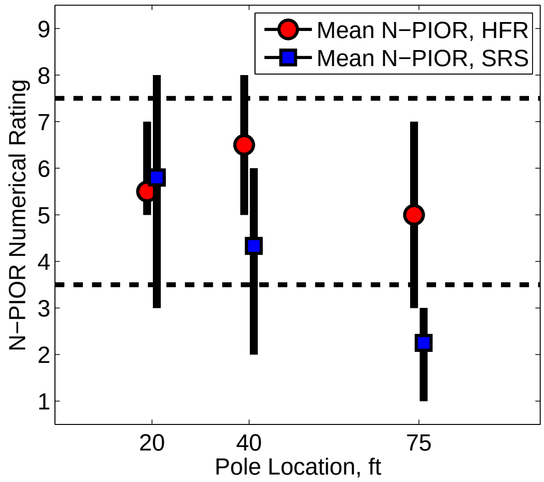


Figure 8: Spread of N-PIOR results for Configuration 4 flown in SRS and HFR.

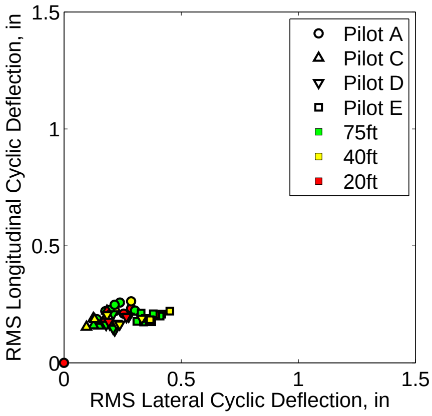
ween the two simulators. Overall, N-PIO ratings suggested much worse conditions were experienced in HQR than in SRS. This is particularly apparent when looking at the spread of ratings for different pole locations. Figure 8 shows the spread and mean N-PIORs for tests completed in both HFR and SRS. For consistency, the ratings shown are only for pilots who completed tests in both HFR and SRS. Here, it is shown that, in SRS, PIOs were not perceived during the PH manoeuvre with the pole located at 75ft. This does not reflect either the predictions or results from HFR. In HFR, N-PIORs awarded included 7D, representing severe oscillations which the pilot considered to be divergent during completion of the task. However, if results from SRS only were used, no PIO potential is recognised with the pole location at 75ft. However, one can see from results that when the task tolerances are tightened, the mean ratings between simulators become more consistent. Results still show a larger spread for results obtained within SRS. However, now RPCs have been recognised in both simulators, which now agrees with the predictions.

The large difference in ratings for the 75ft case appears to be a function of the limited visual cues in SRS. Here, pilots have not exerted the same level of tight closed-loop control as in HFR. As a result, pilots have not triggered the necessary conditions for PIOs to develop. The pilot gain is reduced, limiting the exposure to possible trigger conditions for a PIO during the manoeuvre. As shown in Fig.6, there was significantly less translational rate cueing in SRS, meaning that pilots were less inclined to correct for lateral and longitudinal drift. This difference however is not shown for the 20ft case.

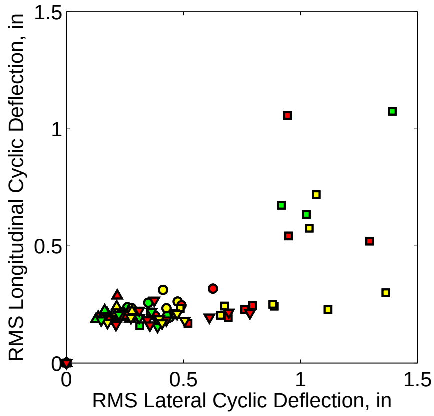
For both simulators, consistent N-PIORs were awarded, with only one 'non-PIO' rating awarded for all tests. Bringing the pole closer to the pilot has increased the emphasis on the forward visual cue, and reduced the emphasis offered by the ground references. In this way, it has improved the consistency of results obtained within the simulation environments.

The effect of changing PH tolerances is further shown in Figure 9. Here, the Root Mean Square (RMS) outputs for pilot control and vehicle output are shown for all configurations flown in HFR. As shown, for all PH completed in the baseline vehicle, all pilots have similar RMS control inputs, producing similar vehicle output response. However, for the PIO prone configurations, RMS input for both longitudinal and lateral control are much more widely distributed. As shown, Pilot E applied the largest control inputs, and was generally the most aggressive when encountering RPCs. The distribution of points shows that, although not a guarantee, the tighter task performance had more chance of causing both higher pilot control input and vehicle rate output for the PIO prone configurations. As this trend is not shown for the PIO robust case, the increased control activity and vehicle rate outputs is not due simply to the task performance requirements, and indicates the triggering of oscillations.

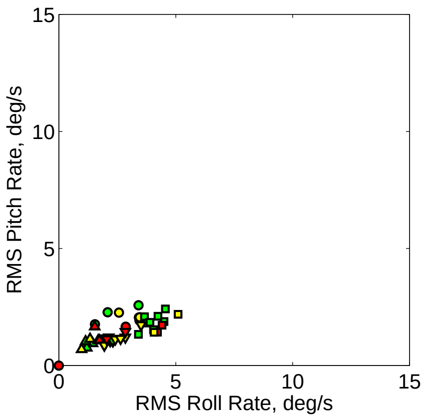
Finally, Fig. 10 displays a breakdown of percentage of cases where N-PIOR >3 was awarded with respect to simulator and pole location. Here, N-PIOR >3 denotes 'oscillations'. Therefore, results show what proportion of cases for each configuration lead to perceived PIOs. As shown, for both simulators, an increase in the percentage of cases leading to PIO >3 is shown for all configurations. PIO ratings for Configuration 1, where no PIOs are predicted, are consistent. This shows that when no trigger is placed within the simulation model, the potential for PIO does not appear to be affected by task performance requi-



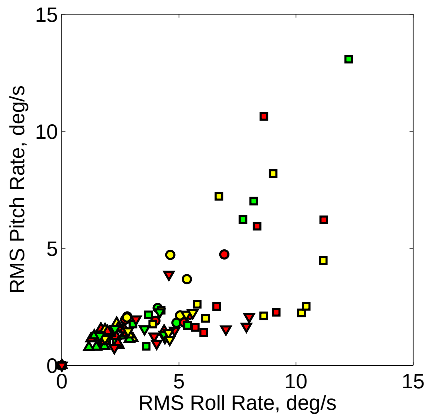
(a) RMS Long. Cyclic wrt Lat. Cyclic for baseline conf., PH



(b) RMS Long. Cyclic wrt Lat. Cyclic for PIO prone conf., PH



(c) RMS Pitch Rate wrt Roll Rate for baseline conf., PH

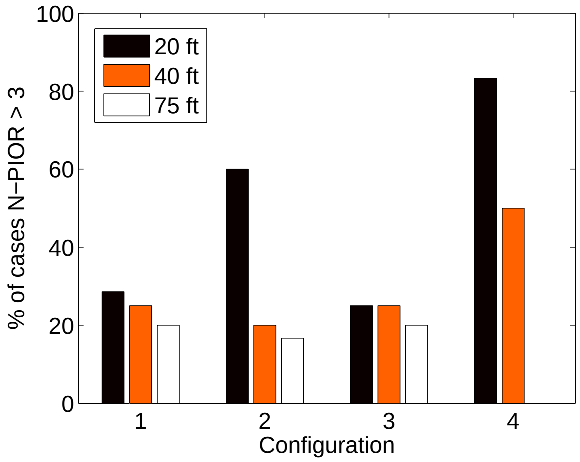


(d) RMS Pitch Rate wrt Roll Rate for PIO prone conf., PH

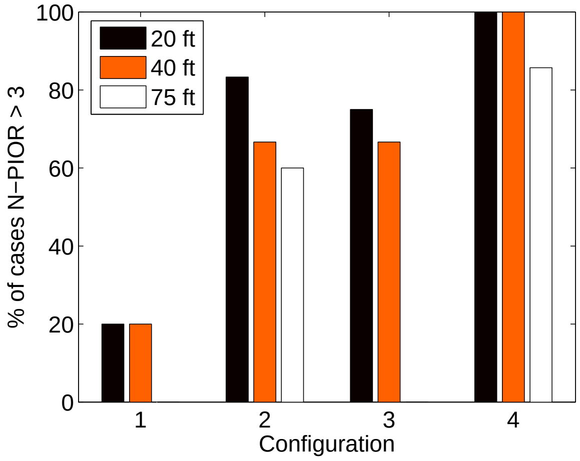
Figure 9: RMS Control and Vehicle Output comparisons for Precision Hover manoeuvres completed in HFR.

rements. Results shown for SRS and HFR in Fig. 10 should not be compared directly, as results are presented for different pilots.

Overall, with the pole location closest to the vehicle, the consistency of triggering PIOs was much higher. HQRs predominantly within Level 2 (shown in Table 3) for Configuration 1 suggest that this task is not entirely removed from the requirements of the rotorcraft. Although the task performance standards may be higher than is usually required for regular flying tasks, setting the difficult performance standards helps to detect the underlying RPC tendencies that could be exposed during extreme flight conditions. For example, in difficult conditions, the pilot may be forced into tight loop control and it is important that the PIO tendencies are known. As stated in Ref. [25],"Pilot evaluations for (APC) tendencies should increase the pilot gain or workload and so increase the possibility of finding hidden (APC) tendencies.". Although these experiments show an increase in detection of PIOs when task performance standards for the PH manoeuvre are changed, the changes are not necessarily appropriate for different rotorcraft. For the original PH manoeuvre, in HFR and with the baseline vehicle configuration, Level 1 HQRs were awarded. Furthermore, during the stabilisation element of the task, pilots were able to go 'open-loop', due to the stable nature of the model. Therefore, tolerances were reduced in order to force pilot gain, and force closed-loop control during stabilisation. However, for vehicles with poorer handling, it may not be necessary to modify the tolerances. The suggestion is that one should complete a number of tests and observe awarded HQRs to judge whether tolerances must be adjusted to look specifically at PIO tendencies. Defining the process for this judgement is a recommendation for further research effort.



(a) N-PIOR awarded in SRS, Precision Hover manoeuvres



(b) N-PIOR awarded in SRS, Precision Hover manoeuvres

Figure 10: Percentage of Cases where N-PIOR > 3 was awarded with respect to hover course.

2.4 Experience using New PIOR scale

The 2nd RBTC was the first time the N-PIOR scale was used for a complete online simulation trial. During the campaign, the scale was always used alongside HQR and PIOR ratings. This helped to jusitfy and benchmark the results obtained. A full comparison of results obtained from the use of the new scale, along with comparisons between traditional ratings is to be presented in detail in a further publication. However, some key findings through its first use are shared here.

For the tasks completed, pilots unanimously preferred the use of the new scale. In particular, pilots felt that the descriptive terms and the decision tree were no longer conflicting. The added subjectivity in the scale required the pilots to give more thought to the rating awarded. Whilst this may have added to their mental workload, the valuable information obtained from their thought processes adds to the usefulness of the ratings awarded. Pilots did comment, however, that in the current form, the scale perhaps suffers from significant non-linearity between ratings 4-7, and they found it difficult to judge the difference between motions and oscillations. Descriptive terms added to the lower right corner of the scale aided the pilots. Finally pilots liked the fact that they were rating oscillations primarily based upon severity rather than convergence/divergence. However, severity is a subjective element within the tree and it is important that pilots are aware of 1) what constitutes a PIO and 2) what is meant by the relative severity.

Overall, N-PIO ratings awarded through the use of the new scale were considered to adequately describe the situations observed, with no major anomalies found during the tests. Furthermore, the results obtained reflected the off-line predictions made prior to the test campaign. This is illustrated through the application of the verification procedure presented in Ref. [26]. Table 4 displays a key for the validation method. Outcomes B and D describe the situation where there is a match between the PIO prediction and the resultant subjective rating.

Table 4: Evaluation of PIO detection

Number of Cases		Simulator Test PIO	
		NO PIO	PIO
PIO Prediction	NO PIO	B	A
	PIO	C	D

The effectiveness of the PIO criterion in predicting PIO can be evaluated according to the following performance metrics;

I1 = Global Success Rate, (B+D)/(A+B+C+D), the percentage of cases which are correctly predicted to be PIO free or prone

I2 = Index of Conservatism, D/(C+D), the percentage of cases predicted PIO prone which have actually undergone PIO in reality with respect to the total number of predicted PIO prone cases

I3 = Safety Index, D/(A+D), the percentage of cases which are predicted by the criterion to be PIO prone, with respect to the total number of simulator test PIO cases.

Table 5 displays the results from the application of the verification criteria, from results obtained in HFR. Numbers within the table show number of occurrences for each pilot, with final percentages shown for all pilots. Results are separated for each reference pole location. It is shown that as the reference pole is brought closer to the vehicle, the Global Success Rate, and Index of Conservatism both improve, and are both above 80%. This is considered to be good correlation, and shows consistency between the off-line predictions and the on-line subjective assessment.

Table 5: N-PIO Ratings for the Precision Hover Manoeuvre, HFR

Precision Hover	75ft	40ft	20ft
Pilot	A,C,D,E	A,C,D,E	A,C,D,E
B	2,1,1,2	1,1,0,1	3,1,0,1
D	2,1,3,2	2,1,3,3	1,4,5,2
B+D	4,2,4,4	3,2,3,4	4,5,5,3
A	0,0,0,0	0,0,1,0	0,0,1,0
C	2,2,1,2	1,2,1,0	2,0,0,0
I1	67%	71%	85%
I2	53%	69%	86%
I3	100%	90%	92%

2.5 Recommendations from the 2nd RBTC

Overall, the results obtained in the 2nd RBTC were considered to improve upon those obtained in the 1st RBTC. However, improvements that could still be made to the test procedure during the trial and analysis were recognised. Some of these are considered below;

First, although the N-PIOR scale offered significant improvements to the traditional scale, some minor changes to the scale could be implimented to further improve the understanding of the results obtained. During the campaign, one rating was obtained for each 'evaluation' run. Whilst the pilots stated in which axis they felt oscillations, this is not explicitly shown through the final N-PIOR. Therefore, one improvement would be to add an additional reference to the axis of concern, or to award ratings for each axis of control.

Second, particularly in SRS, where the limited UCE increased task difficulty, pilots found it challenging to both satisfy the task performance requirements and assess PIO tendencies. Furthermore, the more challenging the task, the more difficult the pilots found to separate their active 'driven oscillations' to those which drove them. Therefore, a strong indication of task performance either during, or after the completed evaluation runs, would improve consistency amongst the subjective ratings. This feedback would allow pilots to ensure that they are flying the manoeuvre to the correct aggression.

Third, it is still considered important that objective measures are used to verify pilot subjective opinion. Subjectivity means pilots assess their experiences differently. One pilot may feel that the resulting oscillations are controlled, and are not 'PIOs'. Therefore, objective measures should be used during test campaigns in order to verify pilot ratings near real-time. The inclusion of detection algorithms during simulation campaigns, such as the Phase-Aggression Criterion (Ref. [27]) or Real-Time Oscillation VERifier (ROVER, Ref. [28]) could assist pilots in their assessment.

Finally, although modification of the PH manoeuvre increased consistency between the predicted and experienced PIO tendencies, piloting strategy was still found to allow for low-gain control activity during the stabilised hover. Pilot D, who employed an 'open-loop' control strategy throughout the test campaign, was able to avoid any 'Severe PIOs' for all Precision Hover configurations. Consistently backing out of the control loop prior to the resultant oscillations, the pilot successfully managed to complete the task within the performance requirements. Therefore, to counteract this, it is suggested that further modifications could be implemented to force high pilot gain. One possible modification would be to replace the inner region of the hover board with a target. The pilot would then be required to keep closed-loop control by keeping the reference point in the centre of the hover board.

3 INVESTIGATION OF AEROELASTIC RPC USING REAL-TIME SIMULATION

3.1 Overview

Rotorcraft-Pilot Coupling (RPC) phenomena that occur at aeroelastic frequencies (2 Hz to 8 Hz, as proposed in Ref. [6]) are termed Pilot-Assisted Oscillations (PAO). In this case, the pilot's intervention is involuntary; it is the result of feeding the cockpit vibrations into the control inceptor through the pilot's biodynamics (often termed biodynamic feedthrough, BDFT). To investigate this phenomena, two Aeroservoelastic (ASE) models, of the IAR S.A. Braov IAR330 Puma and the Messerschmitt-Blkow-Blohm (MBB) Bo105, were developed in MASST (Modern Aeroservoelastic State Space Tools, Refs. [29, 30]). These models were created using the technical data reported in Refs. [6, 7, 31]. A complete description of the vehicle models dynamic set-up is reported in Ref. [32].

Within the ARISTOTEL project, one Aeroelastic Test Campaign (AETC) was conducted, led by partners from Politecnico di Milano (POLIMI) and facilitated at the University of Liverpool (UoL). To supplement this campaign, two Biodynamic campaigns were conducted to characterise both professional and novice 'pilots'. During the Biodynamic campaigns, the focus was on measuring the passive pilot response to vehicle disturbance. HELIFLIGHT (Fig. 11, Ref. [33]) was used to provide accelerations to the pilot seat, whilst they were in the control loop. A full description of the setup and results from these tests is explained in Ref. [34]. During the AETC, the identified pilot models were used to predict Aeroelastic instabilities. These predictions were used to design the simulation campaign set-up.

In the AETC, the linearised ASE models, augmented with a simple Stability Control Augmentation System (SCAS), were implemented in state space form in the FLIGHTLAB software environment of HELIFLIGHT. The usual flight simulation engine integrates the dynamics of non-linear vehicle models developed using the Advanced Rotorcraft Technologies (ART) FLIGHTLAB software (Ref. [35]). In the present case, however, linear helicopter models in state space form generated using MASST were loaded into a 'dummy' FLIGHTLAB model to drive the simulator. The real-time simulation output of these models was used to drive the motion platform control system and the external world visualisation. Similarly, real-time simulation inputs were connected to the flight simulator control inceptors.

Figure 11: The HELIFLIGHT “Bibby” Simulator at the University of Liverpool.

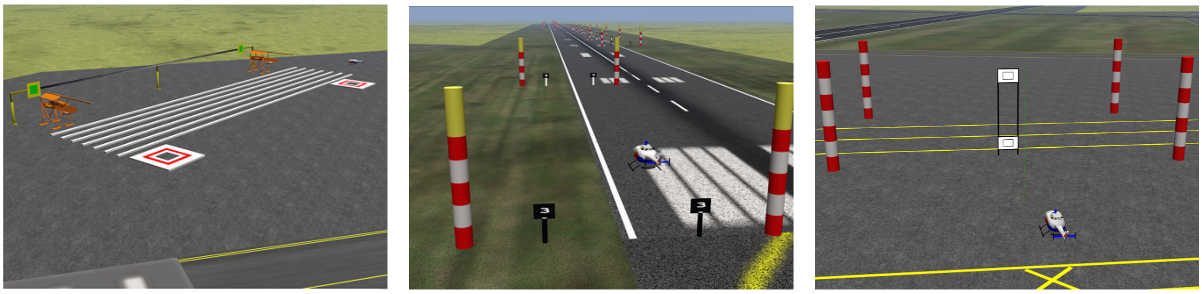
During the AETC, three MTEs were used; the Vertical Manouevre (VM), the Side Step (SS) and the Roll Step (RS) (See Fig.12). These tasks were also used during the 1st RBTC. Three professional test pilots were used during the investigation (A,B,and E). They were all used in the 1st RBTC, and had experience in flying HELIFLIGHT.

The VM and SS manoeuvres were used in order to expose RPCs within the heave and lateral axes respectively during hover. The manoeuvres were taken directly from Ref. [19]. Both tasks required the pilot to initiate a translation from hover, reposition, and then finish again in a stabilised hover. References were provided using specific visual elements within the outside world database. To improve the consistency between the RBTC and the AETC, the same visual database environments were used. The Roll Step (RS) MTE was used to evaluate the lateral dynamics during forward flight. The task was performed at 80kts. The manoeuvre was originally developed for tilt-rotor HQ assessment, and later adapted for helicopters (Ref. [16]).

During the investigation, two pilots (A and B) completed all MTEs in both the Bo105 and IAR330 rotorcraft models. Pilot E completed all MTEs in the Bo105 rotorcraft model. During the investigations, all pilots completed tests in both the ASE models and also the corresponding RB models. This was in order to verify that any RPCs experienced were a direct result of the ASE contribution, and not from the RB mechanics. The RB models used were reduced order variants of the full ASE models developed using MASST. Therefore, the RB and ASE models shared the low frequency flight mechanics elements.

Pilots were asked to provide subjective assessment through the use of the Cooper-Harper HQR scale (Ref. [13]), traditional Pilot-Induced Oscillations Susceptibility Ratings Scale (See Fig. 2) and the Bedford Workload Scale (Ref. [14]). The combination of these subjective ratings was used to assess relative workload, task performance, and RPC susceptibility of the models being flown. After some initial familiarisation runs, each pilot was asked to complete manoeuvres with varying levels of external vehicle disturbance, control gearing, and vehicle time delay. These elements were used in order to trigger ASE RPCs. After completing a number of runs in a given configuration, pilots were asked to give subjective assessment. Results were used to judge the pilot sensitivity to changes, and to tune the next case in order to increase the Pilot Vehicle System (PVS) tendency to induce RPCs.

During the tests, gearing ratios were modified on the collective and lateral cyclic controls through the gains G_z (collective) and G_y (lateral). The largest values of $G_{z,y}$ were four times larger than the nominal values. This represents four times more swashplate deflection per unit deflection of the control. Additional time delays were applied up to 200ms. This was to simulate the effect of a Fly-By-Wire (FBW) system on the closed-loop dynamics of the aircraft.



(a) Sidestep MTE (b) Roll Step Manoeuvre MTE (c) Vertical Manoeuvre MTE

Figure 12: Mission Task Elements completed during the Aeroelastic Test Campaign.

3.2 Influence of Pilot/Lateral Stick Control Feedback in Forward Flight

During the investigation, results involving PAO occurrences were obtained for roll axis dynamics. The RS manoeuvre, performed with the ASE Bo105 at 80 kts, showed a PAO instability as a result of an aeromechanical instability (air resonance) created by the lightly damped main rotor regressive lead-lag mode at 2.26 Hz, coupled with the pilot biodynamics/lateral stick dynamics.

Some of the time histories and Power Spectral Densities (PSD) of the test cases corresponding to the configurations presented in Table 6 are shown in Fig. 13 and Fig.14. Tests have been performed at different control gearing ratios and time delays on the lateral cyclic control. During the RS manoeuvres, performed by pilots A and B, only the lateral disturbance force was active to excite the pilot dynamics in the lateral direction.

Table 6: Bo105 - Roll Step

#	Pilot	Model	Gearing [n.d.]	Delay [ms]
15.1	A,B	ASE	$G_y = 1.0$	$T_y = 0$
15.2	A,B	ASE	$G_y = 2.5$	$T_y = 0$
16.1	A,B	ASE	$G_y = 2.5$	$T_y = 100$
16.2	A,B	ASE	$G_y = 3.0$	$T_y = 100$
18.PAO_P	A,B	ASE	$G_y = 3.0$	$T_y = 100$

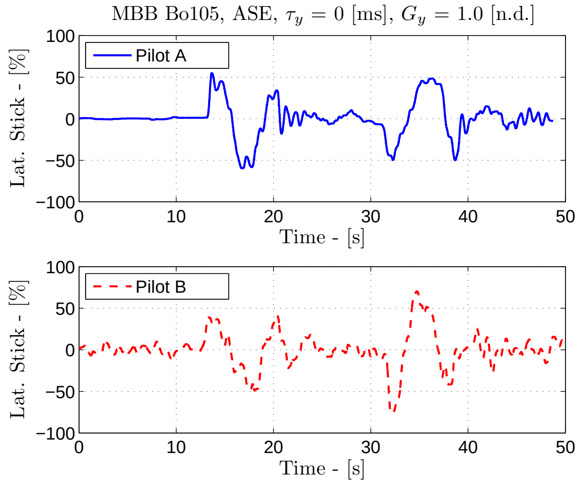
The set of flight simulator parameters that led to PAO conditions with the ASE models are indicated as PAO_p. For each ASE model, the identified PAO_p set was applied to the corresponding RB model to understand the role of higher-order dynamics on the observed phenomenon. In fact, a PAO phenomenon should not appear when using a RB model if the phenomenon is intrinsically associated with the ASE degrees of freedom.

In case 15.1 the gear ratio is nominal and no time delay is present on the lateral cyclic control. The ASE model is used. The PSD of the pilot controls, Fig.13(b), shows that the pilots' activity on the lateral cyclic is confined to below 1 Hz. The biodynamics of the pilots are not excited and no PAO phenomenon occurs.

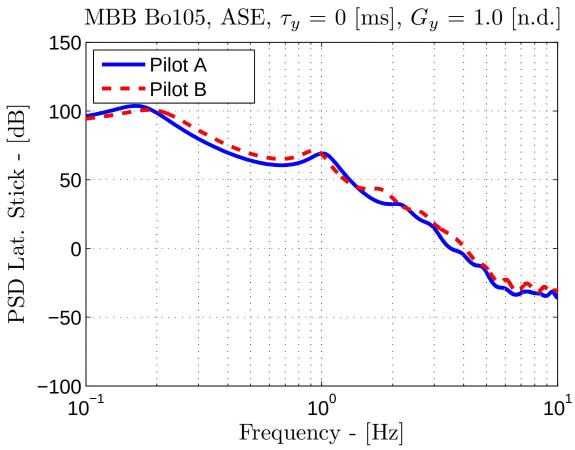
In case 15.2 the gearing ratio on the lateral cyclic control is 2.5 times the nominal value. The pilots are still able to complete the task, even though a PIO phenomenon occurs in the roll axis. The increased activity at 1 Hz, Fig.13(d), is related to the control activity employed by the pilots to stabilise the vehicle in the presence of the PIO instability. No PAO phenomenon, related to involuntary pilot biodynamics, was recorded.

In case 16.1 a 100 ms time delay on the lateral cyclic control was used in addition to the configuration of case 15.2. The activity of all pilots at 1 Hz is still observed; when Pilot A is considered, a PAO instability at 2.34 Hz is triggered. Pilot A experiences the vibrations related to the poorly damped 1st lead-lag regressive mode of the main rotor through the cockpit structure. These vibrations are fed through the controls as the involuntary biomechanical feedback related to Pilot A (Fig.13(f)). The time delay appears to be the key factor causing the pilot response to be in phase opposition to the helicopter dynamics. Conversely, Pilot B does not become involved in a PAO instability.

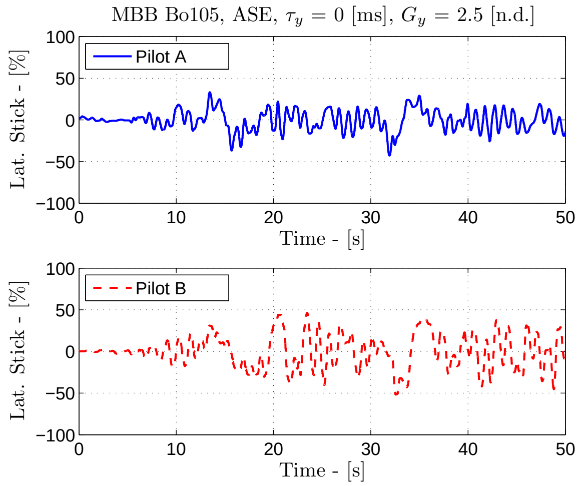
In case 16.2 a control gearing ratio larger than case 16.1 is present on the lateral cyclic control (3 times the nominal value). The time delay of 100 ms has been maintained. This case is characterised by a strong PAO in the roll axis (Fig.14(a)-14(b)) for Pilot A. The PAO phenomenon is the same as that of case 16.1, i.e. related to the time delay on the lateral control. The frequency slightly increases from 2.34 Hz to 2.40 Hz. When the PAO condition is reached, a divergent instability occurs and Pilot A is not able to complete the task. Again, the biodynamics of Pilot B are not excited and the PAO instability observed with Pilot A is not re-



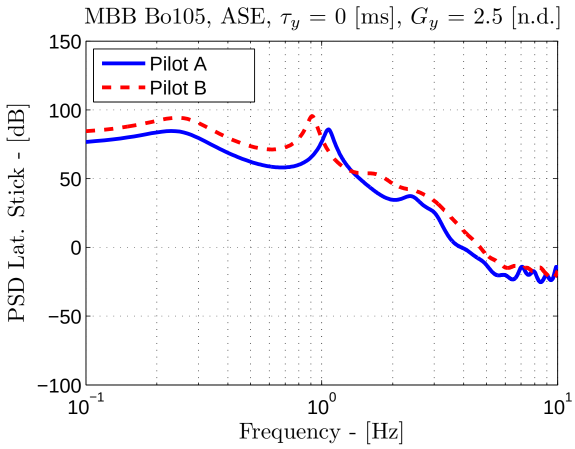
(a) Case 15.1: Time Response - Lateral Stick



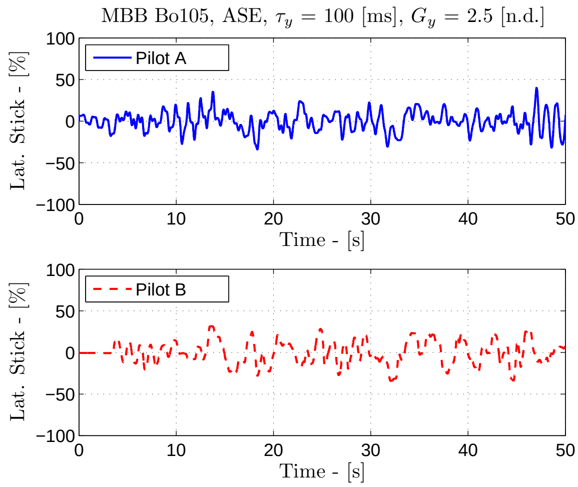
(b) Case 15.2: PSD - Lateral Stick



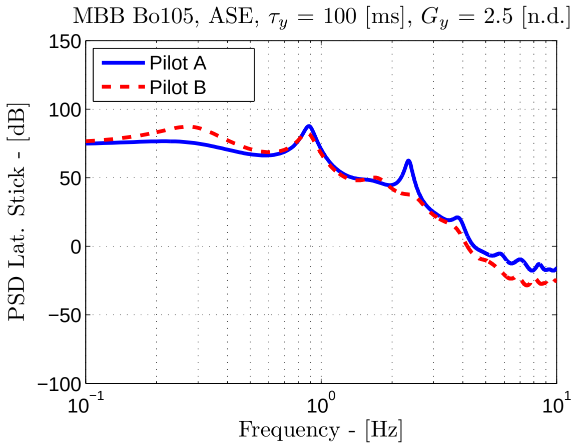
(c) Case 15.2: Time Response - Lateral Stick



(d) Case 15.2: PSD - Lateral Stick

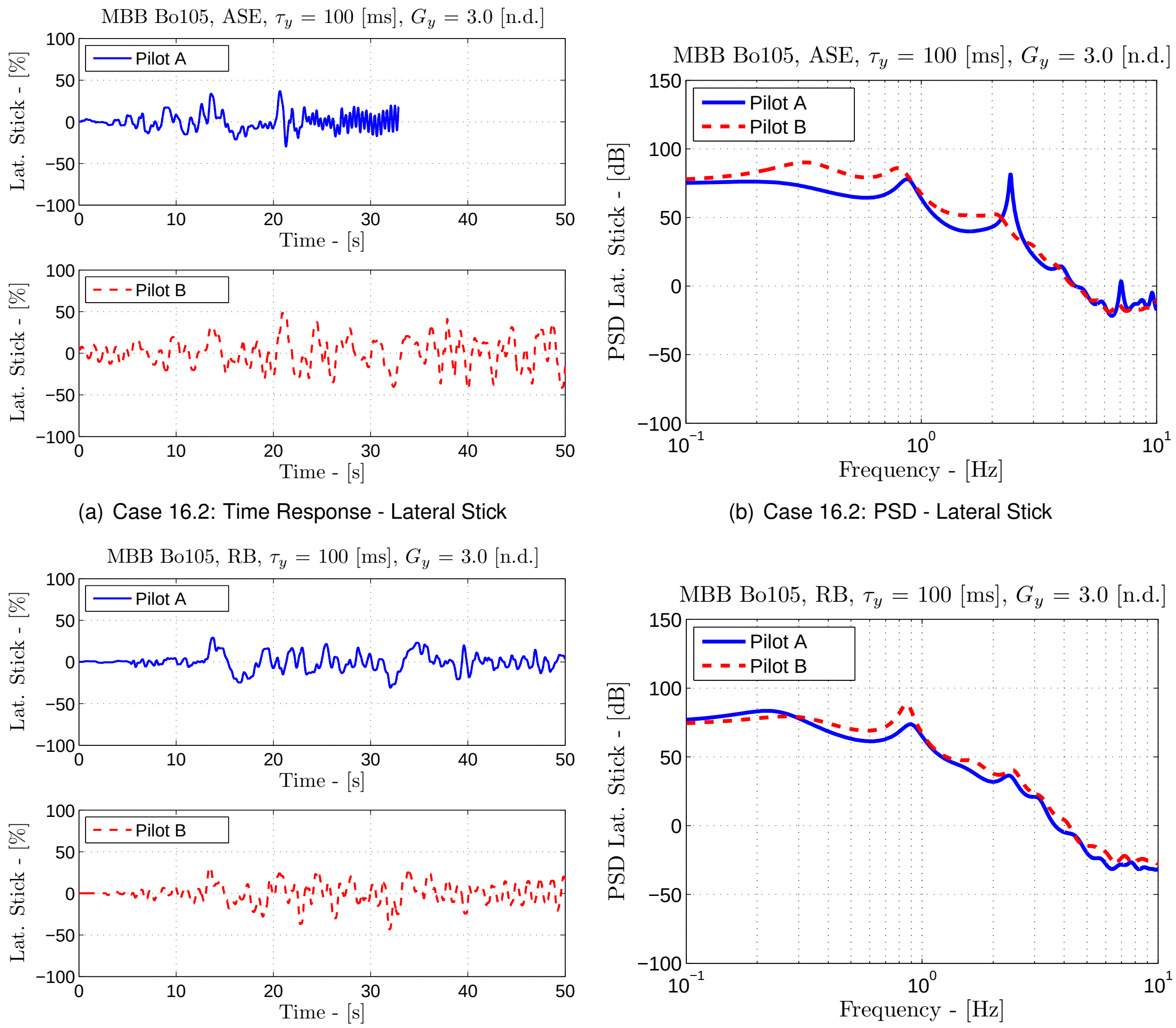


(e) Case 16.1: Time Response - Lateral Stick



(f) Case 16.1: PSD - Lateral Stick

Figure 13: Time histories - PSD of the lateral stick displacement for the tested configurations 15.1, 15.2, and 16.1.



(a) Case 16.2: Time Response - Lateral Stick

(b) Case 16.2: PSD - Lateral Stick

(c) Case 18.PAO$_p$: Time Response - Lateral Stick

(d) Case 18.PAO$_p$: PSD - Lateral Stick

Figure 14: Time histories - PSD of the lateral stick displacement for the tested configurations 16.2 and 18.PAO$_p$.

produced. Case 18.PAOp is the same as case 16.2, in terms of flight simulator set-up, but the RB model has been used instead of the ASE one. In this case no PAO phenomenon occurs (Fig.14(c)-14(d)) with Pilots A and B. The RB model does not contain elastic modes, specifically the lead-lag regressive mode of the main rotor. The pilot biodynamics are not excited, even considering the same gain and time delay of the ASE case. This case provides evidence for the aeroelastic nature of the PAO phenomenon observed in cases 16.1 and 16.2.

3.3 Correlation of Numerical Analysis with Flight Simulator Test Results

PAOs have been predicted using the three pilot/lateral stick transfer functions identified during the experimental test campaign and reported in Ref. [32].

During these tests, the flight simulator was used as a shaker for the test pilots; the motion induced in the control inceptors by the oscillations imposed on the cockpit was measured, along with the motion induced in the limbs. The flight simulator was excited in the lateral direction. To identify the pilot/lateral stick dynamic properties, the lateral acceleration measured on the flight simulator pod, $u(t) = a_y(t)$ (in m/s^2), was used as input, and the lateral stick rotation recorded by the flight simulator, $y(t) = \delta_y(t)$ in (in %) was used as output. Stability analyses were subsequently performed using the Nyquist criterion for Single-Input and Single-Output (SISO) systems, considering the feedback loop between the lateral acceleration at the pilot seat, and the lateral displacement of the stick.

The SISO transfer function of the Bo105 helicopter at 80 kts, $a_y = H(s)\delta_y$, was obtained using MASST. The helicopter transfer function (TF) (including the SCAS dynamics) presents an unstable pole related to the lateral flight mechanics mode (Ref. [32]). Since these dynamics are well separated in frequency from those of interest related to the involuntary pilot response, the helicopter TF has been decomposed into stable and unstable sub-models $H(s) = H_S(s) + H_{NS}(s)$ and only the stable sub-model $H_S(s)$ has been considered in the subsequent analysis.

The Loop Transfer Function (LTF) of the PVS model is

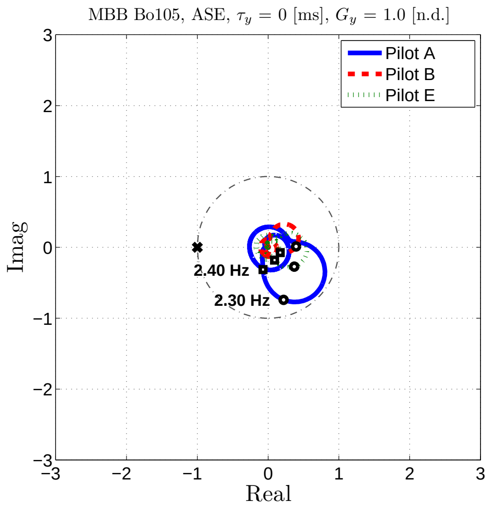
$$LTF(s) = -G_y.e^{-\tau_y s}.H_S(s).H_{PP}(s).H_{WO}(s) \qquad (1)$$

where G_y and τ_y are the gain and the time delay on the lateral cyclic control respectively , $H_{PP}(s)$ is the identified pilot/lateral stick transfer function and $H_{WO}(s)$ is the high-pass filter that accounts for washout of the lateral low frequency/steady acceleration operated by the motion system of the flight simulator. Finally, the minus sign is introduced because the pilot contribution provides a negative feedback loop closure.

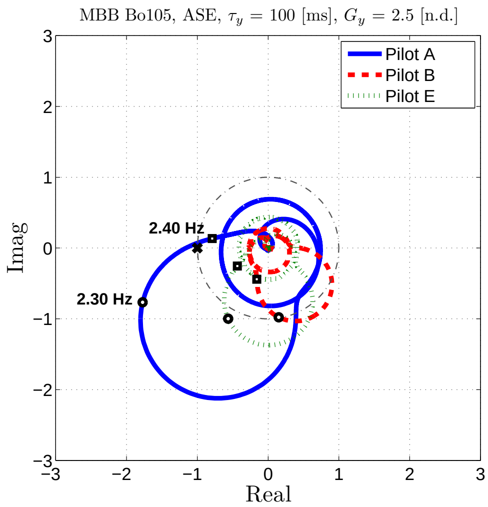
Figure 15 compares the results obtained using models with different gains and time delays, considering the three test pilots biodynamics in feedback loop with the ASE models of the Bo105 at 80 kts.

The configuration with nominal gain and no time delay (Case 15.1) is analysed using the Nyquist criterion in Fig.15(a). The three Nyquist plots are inside the circle of unit radius and the corresponding closed loop systems, considering the three test pilots, are always characterised by robust stability margins.

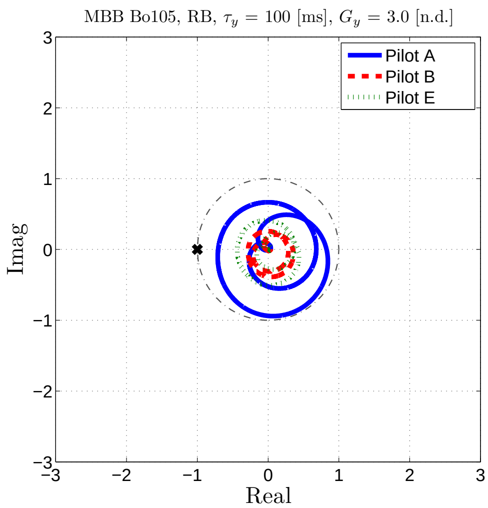
Case 16.1 (Fig. 15(b)) presents larger lateral gearing ratio (2.5 times the nominal value) and 100 ms time delay. The increase in the gain alone enlarges the amplitude of the LTF. This single effect is not sufficient to destabilise any of the closed loop systems. The time delay produces a clockwise rotation of the Nyquist curves, that results in a significant reduction of the phase margin, driving Pilot A towards the PAO instability observed during the experimental test campaign. The Nyquist plot of Pilot A shows that the control system time delay is the key factor that generates the pilot response in phase opposition with the helicopter dynamics. Moreover, the negative gain and phase margins related to Pilot A occur between 2.3 Hz



(a) Case 15.1



(b) Case 16.1



(c) Case 18.PAO$_p$

Figure 15: Nyquist plots of the LTF for the three test pilots in feedback loop with the Bo105 at 80kts.

and 2.4 Hz, which are in perfect agreement with the measured frequencies of the PAO instability observed during the tests.

The Nyquist plot of the LTF resulting from the RB model of the Bo105 in feedback with the three test pilots is shown in Fig. 15(c). Although the largest lateral cyclic gain ($G_y = 3.0$) and time delay of 100 ms were used, the RB model curve does not violate Nyquists stability criterion, since the RB model does not contain the elastic degrees of freedom required to destabilise the closed loop PVS model. Specifically, the lead-lag regressive mode of the main rotor is absent. In such case all test pilots yield a stable PVS, according to the Nyquist plots.

4 CONCLUSIONS

The following are the key conclusions from research presented in this paper;

•Key problems with current testing methods for RPC investigations have been identified by members of the ARISTOTEL consortium. Within 2 RBTC and 1 AETC, efforts have been initiated to solve these problems through application of novel test techniques and procedures.

•In the 1st RBTC, an appraisal of tasks previously used for RPC investigations was undertaken. In this investigation, it was shown that some manoeuvres were unsuitable for exposing RPC tendencies in simulation devices used in the ARISTOTEL project.

•Alterations to the Precision Hover performance standards have improved the overall correlation between PIO predictions and PIO events in flight simulation. Changing the reference pole location on the test course has forced an increase in pilot gain, making the Pilot-Vehicle System (PVS) more incipient to PIO.

•Linearised ASE models, representative of helicopters in hover and forward flight have been flown in a full motion flight simulator, and evaluated by test pilots through the completion of a number of MTEs. During these evaluations, clear evidence of Pilot-Induced Oscillations has been found whilst performing the roll step manoeuvre with a soft-in-plane hingeless helicopter characterised by a lightly damped main rotor first regressive lead-lag mode.

•Repeatable Pilot-Assisted Oscillation (PAO) events were observed with one test pilot flying an ASE model for specific degradations of the control system parameters. Further investigation, requiring the identification of the biodynamic feedthrough of the pilots, indicated that the vicinity of the pilot's biodynamic poles and of the main rotor first regressive lead-lag mode resulted in a reduction of the phase margin that was not observed with the other pilots, which are characterised by slightly higher (and more damped) biomechanical modes.

ACKNOWLEDGMENTS

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement N. 266073.

REFERENCES

[1] Pavel,M. D.,Jump,M., Dang.Vu,B., Masarati,P., Gennaretti,M.,Ionita,A., Zaichik,L., Smaili,H.,Quaranta,G., Yilmaz,D.,Jones,M., Serafini,J., Malecki,J.,"Adverse Rotorcraft Pilot Couplings-Past, Present and Future Challenges", Progress in Aerospace Sciences, [accepted for publication],2013

[2] Pavel, M. D., Malecki, J., DangVu, B., Masarati, P., Gennaretti, M., Jump, M., Jones, M., Smaili, H., Ionita, A., and Zaicek, L., "Present and Future Trends in Aircraft and Rotorcraft Pilot Couplings — a Retrospective Survey of Recent Research Activities within the European Project ARISTOTEL," *37th European Rotorcraft Forum*, Gallarate, Italy, September 13–15 2011, Paper no. 116.

[3] Pavel, M. D., Malecki, J., DangVu, B., Masarati, P., Quaranta, G., Gennaretti, M., Jump, M., Smaili, H., Ionita, A., and Zaicek, L., "Aircraft and Rotorcraft Pilot Coupling: a survey of recent research activities within the European project ARISTOTEL," *3rd CEAS Air & Space Conference*, Venice, Italy, October 24–28 2011.

[4] Pavel, M. D., Malecki, J., DangVu, B., Masarati, P., Gennaretti, M., Jump, M., Smaili, H., Ionita, A., and Zaicek, L., "A Retrospective Survey of Adverse Rotorcraft Pilot Couplings in European Perspective," *American Helicopter Society 68th Annual Forum*, Fort Worth, Texas, May 1–3 2012.

[5] Anon.,"Joint Aviation Requirements, Helicopter Flight Simulators", Join Aviation Authorities Committee, CO, 2001

[6] Dieterich, O., Gotz, J., DangVu, B., Haverdings, H., Masarati, P., Pavel, M. D., Jump, M., and Gennaretti, M. s.l. "Adverse Rotorcraft-Pilot Coupling: Recent Research Activities in Europe", 34th European Rotorcraft Forum, 2008.

[7] Padfield, G. D. "Helicopter Flight Dynamics: The Theory and Application of Flying Qualities and Simulation Modelling. s.l.," Blackwell Publishing, 2007.

[8] Jones,M.,Lu,L.,Jump,M.,Yilmaz,D.,Pavel,M.,Dang Vu, B.,"Deliverable 2.2: Rigid Body Helicopter Model Implementation Report, ARISTOTEL Project, ACPO-GA-2010-266073, 2011

[9] Stroosma,O., Van Paassen,M.M., Mulder,M.,"Using the SIMONA research simulator for human-machine interaction research," AIAA Modeling and Simulation Technologies Conference and Exhibit, 2008

[10] White,M., Perfect,P., Padfield,G.D., Gubbels,A.W., Berryman,A.C., “Acceptance testing and commissioning of a flight simulator for rotorcraft fidelity research”, Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering,Vol.227, Issue 4, pp 663-686, April 2013

[11] Yilmaz,D., Jones,M.,“Deliverable 4.6: Simulator test data analysis of the 1st test campaign, ARISTOTEL Project, ACPO-GA-2010-266073, 2011

[12] Pavel,M.,Yilmaz,D.,Dang Vu,Binh.,Jump,M., Jones,M. ,Lu,L., Adverse Rotorcraft-Pilot Couplings - Modeling and Prediction of Rigid Body RPC - Sketches from the work of European Project ARISTOTEL, 39th European Rotorcraft Forum, Moscow, Russian Federation, 2013.

[13] Cooper,G.E., Harper,R.P., “The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities, AGARD Report 567, NATO, Neuilly-sur-Siene, France, 1969

[14] Roscoe, A. and Ellis, G. s.l.,“A subjective rating scale for assessing pilot workload in flight: A decade of practical use,” TR 90019, 1990.

[15] Jump,M.,Hodge,S.,Dang Vu,B. et al.,“Adverse Rotorcraft-Pilot Coupling: Test Campaign Development at the University of Liverpool,” 34th European Rotorcraft Forum, RAeS, Liverpool, UK, 2008

[16] Cameron, N. and Padfield, G. D. s.l, “Handling Qualities Degradation in Tilt-Rotor Aircraft Following Flight Control System Failures,” 30th European Rotorcraft Forum, 2004.

[17] Jones, M., Jump, M., Lu, L., Yilmaz, D., and Pavel, M. D. s.l., “Using the Phase-Aggression Criterion to Identify Rotorcraft Pilot Coupling Events,” 38th European Rotorcraft Forum, 2012.

[18] Mitchell,D. G., “Flight and Ground Testing fro Pilot-Induced Oscillations”, IEEE Aerospace Applications Conference Proceedings, Snowmass at Aspen, CO, USA, 1999

[19] Anonymous. “Performance Specification, Handling Qualities Requirements for Military Rotorcraft,” Redstone, Alabama, ADS 33-E-PRF, US Army, AMCOM, 2000.

[20] Hodge,S.,Perfect,P.,Padfield,G.D, White,M.,“Optimising the Vestibular Cues Available from a Short Stroke Hexapod Motion Platform,” 67th American Helicopter Society Annual Forum, Virginia Beach,VA,2011

[21] Anon.,“Flying Qualities of Piloted Aircraft,” Department of Defense, United States of America, 1997.

[22] Mariano,V., Guglieri,G. and Ragazzi,A.,“Application of Pilot Induced Oscillations Prediction Criteria to Rotorcraft,” American Helicopter Society 67th Annual Forum, AHS, Virginia Beach, Virginia, 2011.

[23] Duda,H.,“Effects of Rate Limiting Elements in Flight Control Systems - A New PIO Criterion,” AIAA-Paper-95-3304, Aug. 1995.

[24] Yilmaz,D., Dang Vu,B., Pavel,M.D., Jones,M.,“PIO Susceptibility Accompanying HQ Prospects in Preliminary Rotorcraft Design”, 39th European Rotorcraft Forum, Moscow, Russian Federation, Sept. 2013

[25] McRuer,D. T., Droste,C. S., Hansman,R. J., et. al.,“Aviation Safety and Pilot Control: Understanding and Preventing Unfavorable Pilot-Vehicle Interactions ” National Research Council, Washington, D.C., 1997.

[26] Pavel,M. D., Dang Vu,B., Gotz,J., Jump,M. and Dieterich,O.,“Adverse Rotorcraft-Pilot Couplings - Prediction and Suppression of Rigid Body RPC Sketches from the Work of Garteur HC-AG16,” 34th European Rotorcraft Forum, RAeS European Rotorcraft Forum, Liverpool, UK, 2008.

[27] Jones,M., Jump,M. and Lu,L.,“Development of the Phase-Aggression Criterion for Rotorcraft Pilot Couplings,” Journal of Guidance, Control, and Dynamics,Vol.36,No.1,January-Febuary 2013, doi:10.2514/1.58232.

[28] Mitchell,D. G. and Klyde,D. H.,“Identifying a PIO Signature - New Techniques Applied to an Old Problem,” 2006 Atmospheric Flight Mechanics Conference, August 21, 2006 - August 24, American Institute of Aeronautics and Astronautics Inc, Keystone, CO, United states, 2006.

[29] Masarati, P., Muscarello, V., and Quaranta, G. s.l. “Linearized Aeroservoelastic Analysis of Rotary-Wing Aircraft”, 36th European Rotorcraft Forum, 2010.

[30] Masarati, P., Muscarello, V., Quaranta, G., Locatelli, A., Mangone, D., Riviello L., and Vigan L. s.l., “An Integrated Environment for Helicopter Aeroservoelastic Analysis: the Ground Resonance Case”, 37th European Rotorcraft Forum , 2011.

[31] Bousman, W. G., Young, C., Toulmay, F., Gilbert, N. E., Strawn, R. C., Miller, J. V., Maier, T. H., Costes, M., and Beaumier, P. s.l., “A Comparison of Lifting-Line and CFD Methods with Flight Test Data from a Research Puma Helicopter”, TM 110421, NASA, 1996.

[32] Muscarello, V., Masarati, P., Quaranta, G., Lu, L., Jump, M., Jones, M. s.l, “Investigartion of Adverse Aeroelastic Rotorcraft-Pilot Coupling Using Real-Time Simulation,” 69th AHS Annual Forum and Technology Display.

[33] Padfield, G. D. and White, M. D. s.l., “Flight simulation in academia; HELIFLIGHT in its first year of operation,” The Aeronautical Journal of the Royal Aeronautical Society, Vol. 107, (1075), 2003.

[34] Masarati,P.,Quaranta,G.,Zaichik,L., Yashin,Y., Desyatnik, P., Pavel,M., Venrooij, J., Smaili, H., “Biodynamic Pilot Modelling for Aeroelastic A/RPC”, 39th European Rotorcraft Forum, Moscow, 3-6 September, 2013

[35] Anon., “FLIGHTLAB Theory Manual (Vol. One),” Mountain View, California : Advanced Rotorcraft Technology, 2004.

COPYRIGHT STATEMENT

APPENDIX A

This Appendix contains additional tables displaying N-PIOR given by pilots completing the Precision Hover manouevre in both HELIFLIGHT-R (HFR) and SIMONA (SRS). Results are shown with respect to course pole location, and vehicle configuration.

Table A.1: N-PIO Ratings for the Precision Hover Manoeuvre, HFR

		Configuration			
Pole Loc. (ft)	Pilot	1	2	3	4
20	A	1	2	3	7D
	C	3	4A, 5A, 7D	4A	5B, 6C
	D	5C	5B	5B	5C, 5D, 5C
	E	1, 2	7C	7C	8
40	A	2	5C	1	8E
	C	3,3	3	2	5C
	D	5B	3,4C	5B	5B
	E	3	-	5B, 5B, 5C	8D, 8E
75	A	1, 1	2	1	5B, 7D
	C	1	2	2	3
	D	1	5B, 5B	1	5B
	E	2, 2	2	2, 2	8E, 8E, 8

Table A.2: N-PIO Ratings for the Precision Hover Manoeuvre, SRS

		Configuration			
Pole Loc. (ft)	Pilot	1	2	3	4
20	A	1,1,1	2,6D	1	7D,3
	C	3, 3, 5C	6D	5C	6D,8E
	D	3, 3, 3, 5A, 5B, 6B	5B	3	5B
	F	3, 3	3	3	5B
40	A	2	5C, 2	1	2
	C	3,2	3	2	5C
	D	3, 3, 5B, 5B	3	5B	6B
	F	3	3	3	3
75	A	1	3	1, 1	1, 2
	C	2, 2	3	2	3
	D	3, 3, 5B, 5B	3, 3, 5B	5B	3
	F	1, 2, 1	3	3	3