USING THE PHASE-AGGRESSION CRITERION TO IDENTIFY ROTORCRAFT PILOT COUPLING EVENTS

Michael Jones, Michael Jump, Linghai Lu
The University of Liverpool (United Kingdom)

michael.jones@liverpool.ac.uk,
mjump1@liverpool.ac.uk,
Linghai@liverpool.ac.uk

Deniz Yilmaz, Marilena Pavel
Delft University of Technology (Netherlands)

d.ylimaz@tudelft.nl,
m.d.pavel@tudelft.nl

ABSTRACT

This paper describes the application of the newly developed Phase-Aggression Criterion to data obtained during a simulated flight test campaign, in order to assess its suitability to detect Rotorcraft Pilot Coupling events. Due to the increasing complexity of modern rotorcraft, both the frequency and severity of Rotorcraft Pilot Coupling events is envisaged to increase. This concern is also due to the lack of industry guidelines and standards when designing the 'future rotorcraft'. The Phase-Aggression Criterion is a detection tool for these events, capable of achieving a near real-time update of the vehicle's incipience to Rotorcraft Pilot Couplings. Boundaries used by the criteria serve to display severity of any detected 'events'. In this paper, the criterion has been applied to two Mission Task Elements, completed using four test pilots and two motion base simulators. The results presented illustrate good agreement between pilot subjective opinion, output test data and the Phase-Aggression boundary descriptors.

NOTATION

A_G	Aggression, deg/s
H_s	Control system describing function, deg/in
T_{qPK2}	Current time of peak pitch rate, s
$T_{\delta PK1}, T_{\delta PK2}$	Last, current time of peak control input, in
XA	Lateral Control Input, in
XB	Longitudinal Control Input, in
p, q, r	Roll, pitch and yaw rate, deg/s
t_1, t_2	Last, current time step, s
u, v, w	Surge, sway and heave, ft/s
Δ	Change in position, ft
Φ	Phase difference, deg
$\dot{\delta}$	Rate of control inceptor, in/s
ϑ, φ	Aircraft pitch, roll attitude, deg
ϑ_0	Rotor coning angle, deg
ϑ_{1c}	Rotor lateral flapping, deg
ϑ_{1s}	Rotor longitudinal flapping, deg
ϑ_{TR}	Tail rotor coning angle, deg

ACRONYMS

APC	Aircraft Pilot Coupling
A/RPC	Aircraft/Rotorcraft Pilot Coupling
ADS	Aeronautical Design Standard
ARISTOTEL	Aircraft and Rotorcraft Pilot Couplings: Tools and Techniques for Alleviation and Detection
BPD	Bandwidth Phase Delay
EC	European Commission
FoV	Field of View
FT	Flight Test
GARTEUR	Group for Aeronautical Research and Technology in Europe
HFR	HELIFLIGHT-R Research Simulator
HP	High Pass Motion Filter
HQR	Handling Qualities Rating
MCR	Motion Cueing Rating
MTE	Mission Task Element
OLOP	Open-Loop Onset Point
OMCT	Objective Motion Cueing Test
ONERA	Office National d'Études et de Recherches Aérospatiales
PAC	Phase-Aggression Criterion
PIO	Pilot-Induced Oscillations
PIOR	Pilot-Induced Oscillations Susceptibility Rating
PIW	Pilot-Inceptor Workload
PVS	Pilot-Vehicle System
RB	Rigid Body
RMS	Root-Mean Square
ROVER	Real-Time Oscillation VERifer
RPC	Rotorcraft Pilot Coupling
SIMONA	Simulation, Motion and Navigation
SRS	SIMONA Research Simulator
TFCP	Trimmed Flight Control Positions
TUD	Delft University of Technology
FBW	Fly-by-Wire
UoL	University of Liverpool
UCE	Useable Cueing Environment

Presented at the 38th European Rotorcraft Forum, Amsterdam, the Netherlands, September 4 -7, 2012

1. INTRODUCTION

For the purposes of the paper, Aircraft/Rotorcraft Pilot Couplings (A/RPCs) are defined as:

"Unintentional (inadvertent) sustained or uncontrollable oscillations characterized by a mismatch between the pilot's mental model of the vehicle dynamics and the actual vehicle dynamics" [1].

After over 100 years of manned aviation and despite significant investigative efforts, A/RPCs still manifest themselves within current air vehicle operations. Some of the most recently documented RPC events have occurred in the Bell UH-1B and Robinson R44 helicopter types [1].

Historically, research into this phenomenon has focused on Aircraft Pilot Couplings (APCs) in fixed-wing aircraft. During the 1950s and 1960s, many instrumented jet aircraft experienced unfavourable couplings, resulting in the description and characterization of perhaps the most notable form of coupling event that has entered aviation parlance, the Pilot-Induced Oscillation (PIO) [2]. The PIO is a specific type of A/RPC involving low frequency vehicle dynamics (up to 2-3 Hz), where the pilot closes the loop according to the information received through visual or acceleration perception channels. In a PIO, the actions of the pilot cause unintentional vehicle oscillations that have been classified into three categories. Category I oscillations are linear in nature and are often the result of excessive control phase lags. Category II oscillations are described as quasi-linear, where non-linearity arises usually when an actuator rate or saturation limit is reached. Category III oscillations are also non-linear in nature but contain some form of transition, either in the vehicle dynamics (e.g. due to a control system mode change) or in the pilot's behaviour (e.g. due to a change in response to the cues being responded to) [3]. The rapid development of complex control systems, including the increasing use of Fly-by-Wire (FBW) technology has contributed further to the more recent A/RPC problems that have been encountered. Ref. [4] reports that advances in such control systems have contributed to a pilot desensitization, whereby they no longer have a physical connection to the aircraft, which masks the limits of the vehicle controls. A significant proportion of the APC research effort has been expended to try to create predictive methods that will allow the susceptibility to APCs of a vehicle configuration to be identified as early as possible in the design process. For fixed-wing aircraft, there is now a high confidence in using a combination of Bandwidth-Phase delay (BPD) [5-7], Open Loop Onset Point (OLOP) criteria [5, 6] and subjective pilot opinion, to adequately assess PIO potential. For a more complete explanation of BPD and OLOP, the reader is directed to Ref. [2] and Ref. [8] respectively.

Interest in Rotorcraft Pilot Couplings (RPCs) has seen a resurgence in Europe in recent years [5, 6, 9-11]. Due to their large operational envelopes and low stability margins, rotorcraft are potentially more susceptible to unfavourable oscillations than fixed-wing aircraft [4]. Many early fixed-wing PIOs from the 1950s were attributed to low damping in the Short Period and Dutch Roll stability modes [12]. Whilst these modes are often now suppressed in fixed-wing aircraft, their existence is still commonly seen in un-augmented rotorcraft. Furthermore, in rotorcraft, the transfer of pilot control inputs to the main rotor causes transformations from low to high frequency that are often not present in fixed wing aircraft. These transfers are observed at the swash-plate, causing the rotor blades to pitch at a frequency of once per revolution, which has the potential to cause unintended excitation. The first reported incident of a pilot-coupling in rotorcraft is believed to have occurred in the XR-9 in 1945. The pilot was flying the aircraft for the first time, when immediately after take-off the helicopter started to undergo violent oscillations, causing in-phase pitch and rolling motions (a path 45° to the longitudinal axis). The pilot could not regain control of the aircraft and, after 3 violent oscillations, the aircraft crashed to the ground [13]. Since then, there have been a number of high profile RPC incidents. The most complete account of these interactions is contained within Ref. [14]. Although each occurrence is unique, caused by unfamiliar situations and triggers, multiple 'events' have occurred in both the CH-53 and V-22 aircraft during routine testing and operations. In these vehicles, problems have been suppressed through the use of notch filters and/or operational procedures [14]. Interestingly however, no PIO prediction criterion has been specifically developed for the rotary-wing vehicle type. Instead, the applicability of fixed-wing criteria for RPC prediction have started to be assessed as part of work described in Refs. [6, 10].

Of course, even for fixed-wing vehicle types, current offline prediction methods do not guarantee that unfavourable oscillations will not be experienced. Every A/RPC is potentially a one-off event, created by a certain unique individual or set of trigger conditions. Ref. [15] even goes so far as to state that, due to the almost infinite number of trigger situations that can cause PIOs, they will never be fully predictable using 'offline' methods. As a response to this position, real-time detection has been proposed as a means of ensuring flight safety by identifying 'events' as they occur. In this way, the pilot, alerted to the fact that the current vehicle motion is coupled with their control activity, can take some form of preventative action. Current methods for real-time (or perhaps more correctly, near real-time as data has to be sampled and analyzed first) prediction of APCs include Real-Time Oscillation VERifier (ROVER) [12, 16], Wavelet techniques [12, 15] and the Pilot Inceptor Workload criteria (PIW) [17-19]. Whilst the methods have been used in only a limited number of research campaigns, they have demonstrated that real-time prediction is possible. However, the methods must be developed further to establish their effective application to different vehicle types and APC situations. There is also a degree of uncertainty inherent in the use of each of these methods, making it challenging to apply them directly across those same vehicle types and situations. For example, the guidelines for ROVER state that the user must select 'threshold values based on available data' [12]. There is clearly the possibility for results to be misinterpreted if the thresholds have not been set correctly. In the light of these limitations, it was considered that a new technique could be conceived. At the University of Liverpool (UoL), a new real-time detection tool has been developed in order to determine the RPC/PIO incipience of a given rotorcraft, and the severity of any detected events. The new method, named 'Phase-Aggression Criterion' (PAC), uses continuously sampled information from the pilot inceptor and aircraft motion to ascertain the severity of the situation. The development of the criterion is discussed in more detail in Ref. [20].

The research described in this paper applies the previously developed PAC to a new dataset of RPC events found during experiments in two motion-based simulation facilities. Firstly, the formulation and application of PAC is discussed, with boundaries presented from previous simulated tests. Next, a brief discussion of the test campaign is presented, including an explanation of the facilities, models and tasks used. Results from the application of PAC criteria to the dataset are then presented, and its suitability is assessed through comparison with pilot subjective opinion, task performance appraisal and visual inspection. The paper is then drawn to a close with some concluding remarks.

2. FORMULATION OF THE PHASE-AGGRESSION CRITERION

PAC was developed at the UoL in order to act as a real-time RPC detection tool. Its development was initiated to address perceived limitations suffered by existing real-time detection methods. The criterion was developed through the extension of the PIW criteria proposed by Gray, Refs. [17, 18, 21]. The drawback of using the PIW criterion to detect RPCs is the absence of information regarding the dynamics of the vehicle; by only sampling the pilot 'inceptor' inputs, there is no way of knowing if the Pilot-Vehicle System (PVS) is experiencing undesirable oscillations, the result of a mismatch between the pilot mental model and the dynamics of the vehicle. The criterion was adapted and developed in two ways;

- Extension of data sampling to include the dynamics of the vehicle, offering both a measure of the pilot's activity and the resulting vehicle dynamics.
- Modification to 'real-time' sampling of data throughout the flight manoeuvre, using constant pre-defined periods.

The information selected to provide an appraisal of the vehicle's proximity to an RPC event, as the name of the criterion suggests, was the phase difference between pilot input and vehicle output. As the pilot is ultimately interested in achieving a desired attitude, a phase difference of 90° between the attitude rate and inceptor input describes an out-of-phase response (i.e. the attitude lags pilot control by 180°). This is classically one of the important factors required for a PIO to exist.

The parameters used in PAC are described in Eqn. (1) and Eqn. (2). Aggression is taken to be dependent on the rate of demanded control input by the pilot. This was set to be evaluated in intervals (defined as time steps). The Aggression is calculated as the RMS average of the control rate over each of these intervals. In order to relate the Aggression to control channel rate limiting elements, the factor H_s was introduced, the control system describing function (ratio of control surface output to pilot inceptor deflection). For the cases in the subsequent analysis, H_s was approximated to be a pure gain. However, the capability exists for this to be represented by a more complex nonlinear function. It is worth mentioning that limiting elements at the control surface (i.e. effects of system actuators) are used to set boundaries for RPC/PIO detection and, as a result are not included in H_s. The phase between inceptor inputs and vehicle attitude rate was calculated in the time domain. In Eqn. (2), $T_{q_{PK2}}$ and $T_{\delta_{PK2}}$ represent the time of the current peak rate and peak control deflection respectively and $T_{\delta_{PK1}}$ represents the time of the last peak of control deflection. The algorithm to calculate phase difference was set to evaluate peaks in the responses, and calculate both the time difference between the pitch rate and control displacement peaks along with the time difference between control displacement peaks.

(1) $$A_G = H_s \cdot \frac{1}{(t_2 - t_1)} \int_{t_1}^{t_2} \left| \dot{\delta}(t) \right| dt$$

(2) $$\Phi = 360 \left(\frac{T_{q_{PK2}} - T_{\delta_{PK2}}}{T_{\delta_{PK2}} - T_{\delta_{PK1}}} \right)$$

In order to utilise the new criterion as a real-time RPC detection aid, it was decided that both Aggression and phase information should sampled at a (constant) sample rate that was suitable to detect PIOs (there is no point in predicting an event in real time once the event has already occurred). In Eqn. (1), t_2 represents the time at the current calculation time step, whilst t_1 represents the time at the last calculation time step.

For the purpose of this study, the sample rate was kept at a constant 1 Hz. This was considered to be a suitable rate as it allowed for enough meaningful data to be collected for each interval whilst also ensuring that detections were updated based on information from the previous second. When setting boundaries for detection of RPCs, it was only necessary to identify events which would significantly affect the pilot's control of the aircraft. It is not desirable to identify and potentially alleviate every minor pitch bobble, as the system would become more of a hindrance than a help to the pilot. Therefore, when constructing PAC, the following were deemed as key rules for PIO/RPC;

- *Task Performance;* A PIO that is judged to warrant concern is one that has a significantly detrimental effect on overall task performance. The key distinguishing feature that was assessed was to 'filter' the situations where oscillatory responses were a side effect of the pilot's tracking effort, and to identify the oscillations that suggested potential for loss of control. To assist with this analysis, pilot comments in conjunction with subjective opinion ratings were used.

- *Changes in control strategy;* PIOs cause changes in control strategy, whether it is due to applied compensation to arrest oscillations or due to the change in strategy to try and suppress or avoid oscillatory responses.

- *Effects of limiting elements;* A strong indication of PIOs occurring is when any control path rate limits are activated. Whether this is constant or sporadic, non-linearities make it challenging for the pilot to interpret the compensation that is required.

- *Out of phase;* For PIOs, there exists the requirement for the aircraft response to be out-of-phase with the pilot command; that is, a mismatch between the pilot and vehicle dynamics.

It was found that the plot of Aggression with respect to Phase could be used in order to determine the RPC/PIO incipience of completed pilot simulation runs. This was shown through the spread of time dependent Phase-Aggression points. The resulting plot is referred to as the Phase-Aggression chart. In order to define boundaries on the chart, data from a simulated test campaign was post-processed. This campaign was conducted by two pilots, using the Pitch Tracking task discussed later in this paper. The vehicle model used was the FLIGHTLAB Generic Rotorcraft, which exhibits features representative of a currently operational utility helicopter. Variable rate limits were used to trigger RPC/PIOs. A full report of this investigation is given in Ref. [20]. By observing the spread of Phase and Aggression throughout each piloted simulation run, it was possible to isolate regions of the Phase-Aggression chart relating to the occurrence of RPC/PIOs. This was completed, with regions defined for no, moderate and severe PIOs. These are shown in Fig. 1.

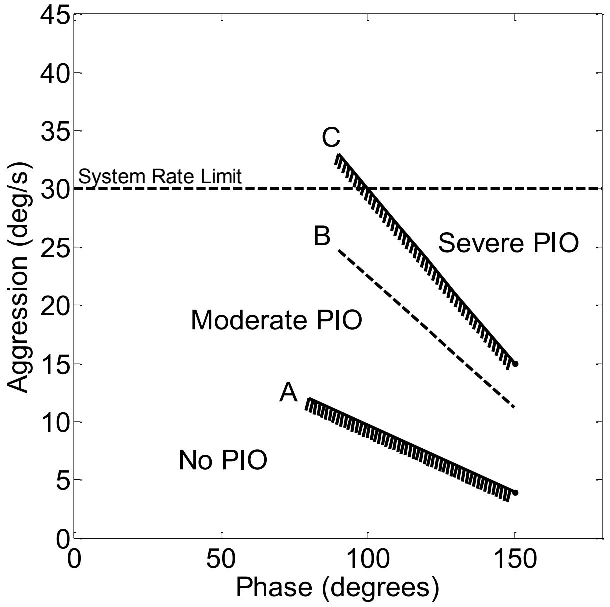

Fig. 1: Proposed Longitudinal Phase-Aggression boundaries

Definitions of the regions are discussed below;

- *No PIO:* In this region, any oscillations shown in the test data relate to pilot demanded oscillations or to mild pitch bobbles. Any oscillations that were experienced did not cause a failure to maintain task performance and did not cause excessive pilot workload during task completion.

- *Moderate PIO:* In this region, PIOs are likely to be experienced as convergent oscillations, characterized by either linear system dynamics or by the activation of quasi-linear behaviour, attributable to system rate limits.

- *Severe PIO:* The pilot is either operating close to or beyond the control system rate limits, applying a high rate of control input during a period where a high PVS phase differences exists. A pilot that does not reduce his gain whilst applying inceptor inputs occurring in this region will likely enter into divergent PIOs, caused by the presence of rate limiting elements i.e. a Category II PIO.

Furthermore, as shown in Fig. 1, boundary B has been applied as a warning margin between the Moderate and the Severe PIO. This acts as a 'buffer' between the linear PIOs and the quasi-non-linear effects of the system rate limits.

In the case shown in Fig. 1, the rate limiting element in this channel is set at 30 deg/s. Boundaries B and C are normalized and positioned based on this value. Boundary A is set constant regardless of the system rate limit value. Boundary C is set such that it intersects the system rate limit at a phase of 100 degrees and at a phase of 150 degrees at half the system rate limit. Boundary B provides a 20% margin to boundary C. A margin of 20% was used due to significant rate limiting in this region. One of the proposed benefits of PAC is the possibility that the boundaries presented are both task and vehicle independent. The inclusion of dynamics of the vehicle control system in the Aggression parameter means that a direct comparison of control surface deflections can be performed. Furthermore, phase difference will be consistent across vehicles; for some vehicles it will be more likely that large phase differences will occur, but the degree to which phase difference causes perceived RPCs should remain fixed.

The boundaries shown in Fig. 1 represent the proposed limits for the combination of A_G and phase difference that lead to PIOs. Using the boundaries, the severity of the oscillations can be observed, by determining the proximity of the results to 'types' of PIOs. Herein lies a potential advantage of PAC when compared to current methods, where it is difficult to assess the actual severity of the event in real-time.

3. FLIGHT-SIMULATION CAMPAIGN OVERVIEW

3.1 Overview of Simulation Models

As part of the EC project ARISTOTEL (Aircraft and Rotorcraft Pilot Couplings: Tools and Techniques for Alleviation and Detection, ACPO-GA-2010-266073), a number of piloted simulation campaigns are due to be completed. These campaigns will focus on the assessment of both Rigid Body and Aeroelastic RPC events. Table 1 shows the distinguishing characteristics of these types of RPC.

This paper reports results from the first ARISTOTEL Rigid Body (RB) test campaign that was jointly undertaken at the UoL and the Technical University of Delft, NL (TUD). During the campaign, four test pilots completed a number of Mission Task Elements (MTEs), most, but not all, of which were either adapted or developed from those contained within Aeronautical Design Standard 33 (ADS-33E-PRF, [22]).

For the purpose of the tests, both UoL and TUD developed simulation models of a 'generic' light rotorcraft. Based on available data contained in the literature, the model dynamics resemble those of the BO105 helicopter (Fig. 2).

Table 1: Characterization of Rigid Body and Aeroelastic RPC events (adapted from Ref. [10])

	Rigid Body RPC	Aeroelastic RPC
Frequency Range	Below 3.5 Hz	Between 2 and 8 Hz
Pilot Behaviour	Active pilot concentrating on the task	Passive pilot subjected to vibrations
Helicopter Dynamics	Low frequency flight mechanics models	Structural dynamics models
Critical Component	Flight control system	Airframe models

Fig. 2: BO105, taken from Ref. [23]

The rotorcraft model used by UoL was constructed using FLIGHTLAB. A full description of FLIGHTLAB, and its uses is contained within Refs. [24-27]. The model consists of 44 states; 18 translational and rotational body states, 4 propulsion states and 22 rotor states, incorporating lead-lag rotation for each individual blade. The model includes rotor stall effects but no interference effects from the main or tail rotors on the airframe.

TUD developed an equivalent RB simulation model using "Maple". Maple is a general purpose algebra system supporting numerical and symbolic analytical computation and visualisation. The model contains 16 states; 6 translational and rotational body states, 3 flapping states, 3 lead-lag states, 3 Pitt-Peters dynamic inflow states and 1 tail rotor inflow state. It was not possible to include stall and root reverse flow in the analytical model. A detailed comparison of the results obtained from both models was required prior to the test campaign. The main reason for this was to validate computational methods used and to check that the models offered comparable responses for the appraisal of RPC susceptibility. Some snapshots of the analysis are shown here. Fig. 3 shows the trimmed flight control positions (TFCP) of both models and flight test (FT) data, obtained from GARTEUR Helicopter Action Group 16. As shown, the models TFCP are not only similar to one another but also show good correlation to the FT data. Fig. 4 shows two on-axis responses to 3-2-1-1 lateral and longitudinal cyclic inputs. Again, the response obtained from both models is compared with data obtained from FT. The on-axis response comparisons in particular show good agreement between the simulation models and the FT data.

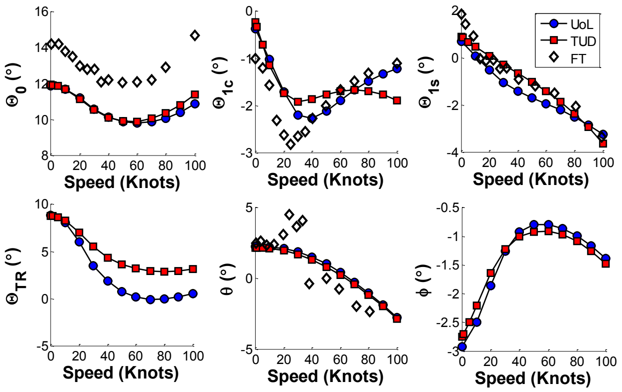

Fig. 3: Comparison of Trimmed Flight Control Positions

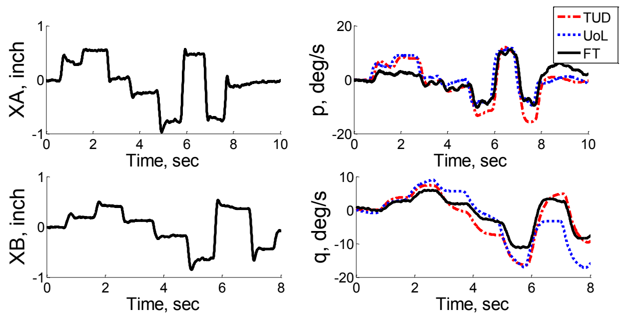

Fig. 4 Response to 3-2-1-1 lateral and longitudinal control inputs

3.3 Test Campaign and Manoeuvres

Using the helicopter flight dynamics models and simulation facilities described above, the test campaign was conducted through co-operation between TUD, UoL and Office National d'Études et de Recherches Aérospatiales (ONERA). The primary goal of the study was to extend the database of simulated RPCs, started during research in GARTEUR Action Group 16 (described within Refs. [6, 9, 10]). A test matrix was developed to investigate RPC potential in the lateral, longitudinal and heave axes of the rotorcraft model. RPCs were triggered using both linear dynamics (i.e. additional control channel time delays) and quasi-linear effects (i.e. actuator rate limits). Four pilots were used in the investigation; their experience is contained in Table 2. During the campaign, the primary method used to identify RPC events was pilot subjective opinion. Handling Qualities Ratings (HQRs), Pilot Induced Oscillations Ratings (PIORs) and Bedford Workload Ratings were collected for all completed test points. For completeness, the PIOR scale [28] used during the investigation is shown in Fig. 5.

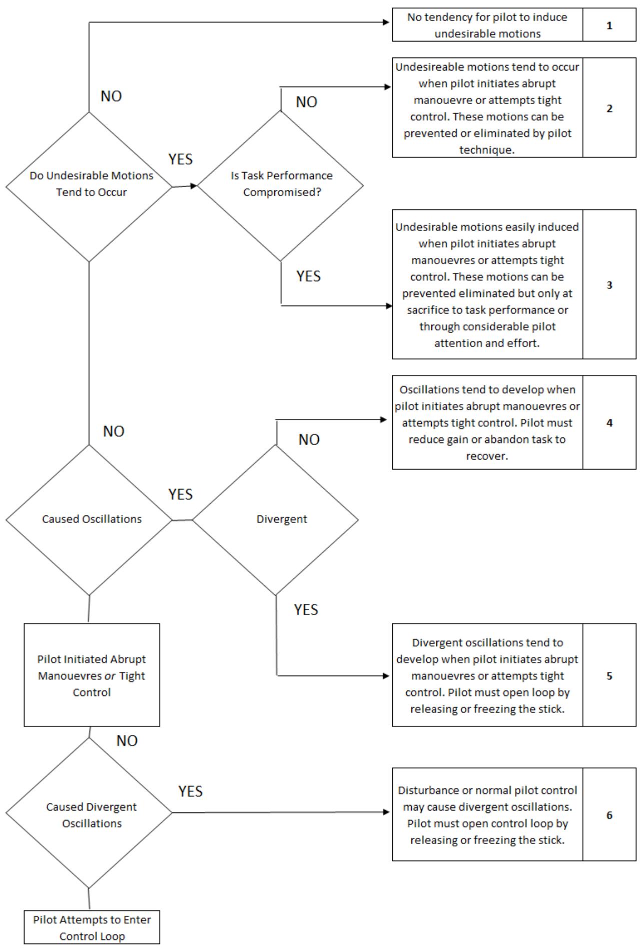

Fig. 5: Pilot Induced Oscillation Susceptibility Rating Scale

During the investigation, candidate manoeuvres, representing rotorcraft Mission Task Elements (MTEs), were selected to expose predicted RPCs. In this paper, data from two of these manoeuvres are used. The following subsections briefly describe these candidate manoeuvres.

Table 2: Pilot experience resume

Pilot	Current Employment	Rotary-wing hours	Fixed-wing hours	Sim hours
A	Senior Captain for Commercial Airline	3000	11000	5000
B	Senior First Officer for Commercial Airline/British Royal Navy	7800	8000	1300
C	Royal Netherlands Airforce – Chinook Test Pilot	1500	200	230
D	Royal Netherlands Airforce – Apache Test Pilot	2000	150	400

3.3.1 Pitch Tracking

An attitude capture task, using the Head-up Display (HUD), shown in Fig. 6, was designed to expose RPCs in the pitch axis. Performance requirements are shown in Table 3. Pilots were required to position the aircraft bore-sight anywhere within the boundaries which were located a visual angle of 5 degrees apart. At 5 second intervals, the boundaries would instantaneously move to a new vertical position in the visual scene. The pilot's task was to reposition the bore-sight between the newly located boundaries within 2 seconds, and stabilise the vehicle pitch motion until the boundaries moved again. This task, where pilots are forced to apply large aggressive control inputs followed by tight control for stabilisation, is similar to the task employed by the German Aerospace Centre (DLR) to expose lateral PIOs [29].

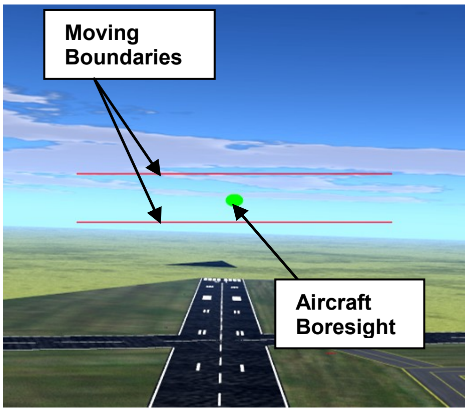

Fig. 6: Pilot eye view of HUD and outside world in HFR simulator

Table 3: Performance requirements for the Pitch Tracking manoeuvre

Performance	Desired	Adequate
Achieve capture of new attitude by positioning bore-sight between boundaries within X seconds	2	2
Maintain bore-sight position between boundaries following capture for X% of time	100	70

3.3.2 Acceleration-Deceleration

The Acceleration-Deceleration manoeuvre was taken directly from Ref. [22] as a candidate task to expose RPCs in the pitch axis. During the manoeuvre, the rotorcraft must transition from hover to 40 knots, and must then be brought back to hover with a nose-up pitch attitude of at least 30°. This must be completed within the tolerances specified in Table 4. It is also a requirement that the rotorcraft reaches 95% of continuous power (or maximum transient limit) after the initiation of the manoeuvre.

Table 4: Key performance requirements for the Acceleration-Deceleration manoeuvre

Performance	Desired	Adequate
Maintain altitude below ±X feet	50	70
Maintain Lateral Track within ±X feet	10	20
Maintain heading within ±X°	10	20
Achieve a nose-up pitch attitude during the deceleration of at least X°	30	10
Longitudinal tolerance on the final hover point is plus zero, minus X ft	21	42

The deceleration and stop to the end hover point is the point where the pilot would enter closed-loop control of the aircraft and, is therefore, of most interest when investigating RPCs. This is where the pilot is likely to be at highest gain during the manoeuvre. As a result, it is likely to be the point at which an RPC might be triggered. Fig. 7 shows a view of the visual database used to complete the Acceleration-Deceleration, whilst Fig. 8 shows the plan view of the course layout. Vertical poles were positioned to provide height cueing, with each stripe representing 10 ft. The rotorcraft is shown at the start point of the manoeuvre. During the transition, it must stay within the central lines of parallel cones for desired performance, and maintain height below the top of the striped poles throughout. The pilot must bring the rotorcraft to the hover prior to the end point, indicated by the final line of cones.

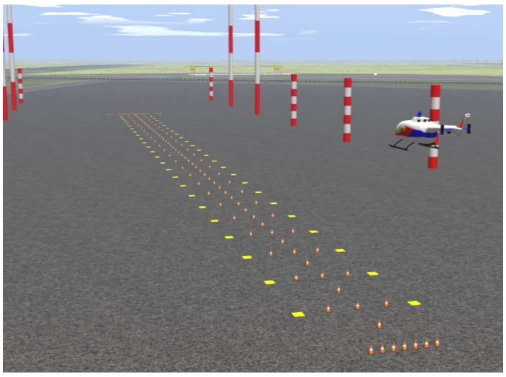

Fig. 7: Example of visual scene for Accel-Decel manoeuvre in HFR simulator

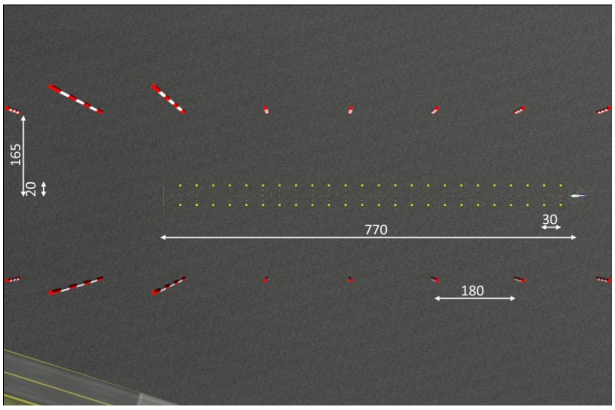

Fig. 8: Plan view of Accel-Decel course (dimensions in ft)

3.2 Simulation Facilities

Two flight simulation devices were used for the investigation; SIMONA Research Simulator (SRS, Fig. 9) at TUD and HELIFLIGHT-R (HFR, Fig. 10) at UoL. A full description of facilities can be found in Refs. [30, 31] and Refs. [32, 33] respectively. Due to differences in the hardware configurations, their capabilities with regards to the delivery of cueing to the pilot are considerably different. Both devices however offer reconfigurable motion cueing and force-feel system dynamics, which were tuned prior to the investigation.

The Field-of-View (FoV) for both HFR and SRS are displayed in Fig. 11. Due to its projected display onto the interior of the dome shown in Fig. 10, HFR offers a greater FoV in both horizontal and vertical directions, with considerable difference to the pilot's right. Restrictions in SRS impacted on the capability of the pilots to adequately assess their performance whilst completing task manoeuvres. Pilot's commented that the 'chin windows' offered by HFR allowed for better task performance, as they provided adequate ground references throughout. Determination of the Usable Cueing Environment (UCE), using the method outlined in Ref. [22] was used to subjectively assess the influence of FoV. UCE's were determined for each task. Results for the Accel-Decel manoeuvre are shown in Fig. 12. Overall, UCE = 1, denoting good translational and attitude cueing, was awarded in HFR, and UCE = 2, denoting only 'fair' cueing, was awarded in SRS. It is for perhaps this reason that, during the Accel-Decel, two of the three pilots awarded higher average Handling Qualities Ratings (HQRs), with a larger spread of results.

Fig. 9: SIMONA Research Simulator (SRS) at Technical University Delft [34]

Fig. 10: HELIFLIGHT-R simulation facility at the University of Liverpool [35]

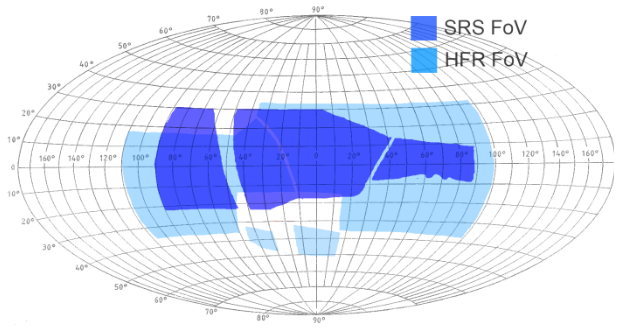

Fig. 11: Comparison of HELIFLIGHT-R and SIMONA FoV

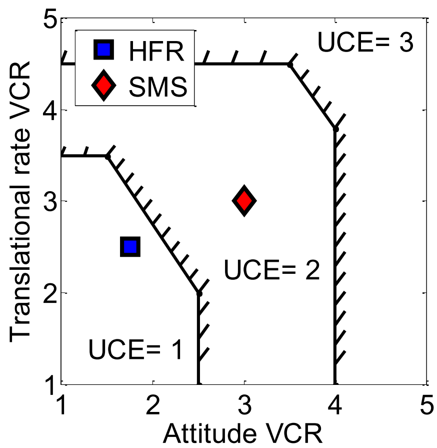

Fig. 12: UCE ratings for the Accel-Decel manoeuvre

The motion systems of both simulators were configured to provide suitable motion cueing using pilot subjective opinion prior to the start of the test campaign. This was to ensure that pilots could adequately complete MTEs, without receiving false motion cues (due to nonlinearities, such as leg saturation). However, during the test campaign, a number of significant differences existed between the motion cueing provided by the simulators. The high pass (HP) filtering used on the motion platforms was different. SRS was configured with 1st order rotational filters, 2nd order surge and sway translational filters and 3rd order heave translational filters. HFR was configured in all axes with 3rd order HP filters.

An appraisal of the relative fidelity of both motion bases is currently being completed, through the application of the Objective Motion Cueing Test (OMCT) procedure outlined in Ref. [36]. This measures response of the motion capabilities at a number of frequencies, and includes consideration of cross-coupling effects (i.e. to account for SRS tilt-sway co-ordination). It was considered that, due to large differences regarding cueing delivered by each axis, application of traditional quantitative measures, such as the Sinacori fidelity criteria [37], would not adequately describe the relative fidelity of the motion systems.

To provide a qualitative appraisal of the overall motion fidelity during the test campaign, Motion Fidelity Ratings (MFR, see Fig. 13), were taken from all pilots during the test campaign. These were taken once for each MTE. Results obtained for the Accel-Decel manoeuvre are shown in Table 5. These are typical of MFRs awarded for other manoeuvres. For all cases, pilots believed that the motion cueing was useful for task completion. Furthermore, on only one occasion were cues rated as unacceptable, causing a loss of performance and disorientation. This was a case flown by Pilot B, where tilt-sway rate limiting caused false cueing during the translation element of the manoeuvre. This problem affected the minority of Accel-Decel tasks performed.

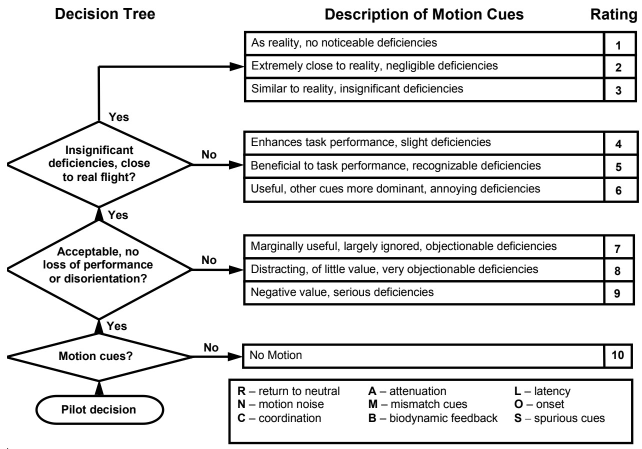

Fig. 13: Motion Fidelity Ratings Scale, taken from Ref. [33]

Table 5: Overview of Motion Cueing Ratings for the Accel-Decel manoeuvre

Pilot	HFR	SRS
A	4	4
B	4	7
C	3	3
D	3	5

The reconfigurable control loaders allowed the two simulators to be configured with the same control force-feel settings. These were set to match characteristics of the DLR Bo105, the aircraft used to obtain FT data shown in Fig. 3 and Fig. 4 on both simulators.

4. RESULTS: APPLICATION AND RESULTS OF THE PHASE-AGGRESSION CRITERION

The criterion described in Section 2 was applied to the MTEs discussed in Section 3. Here, a brief discussion of general results for each MTE is presented, followed by an analysis of the effectiveness of the Phase-Aggression Criterion in detecting observed 'events'.

4.1 PAC identification of RPCs during the pitch tracking manoeuvre

All Pitch Tracking test runs undertaken on HELIFLIGHT-R were post-processed using PAC. The boundaries shown in Fig. 1 were used to detect RPC events that occurred in the longitudinal axis during the completion of the manoeuvre. Fig. 14 and Fig. 15 display the overall HQRs and PIORs obtained during the investigation with respect to the longitudinal channel rate limits.

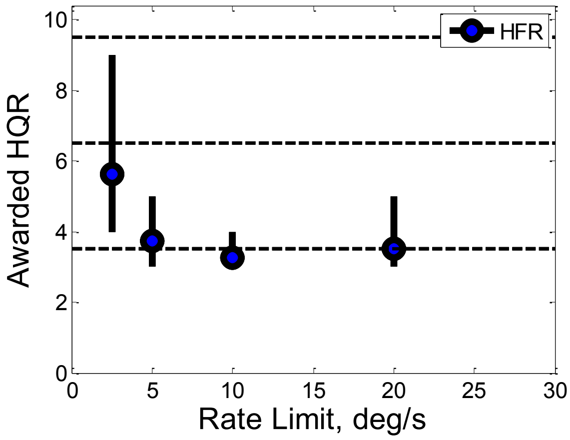

Fig. 14: Awarded HQRs with respect to longitudinal rate limit

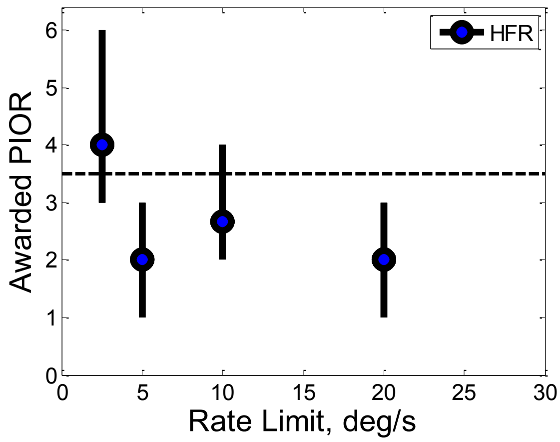

Fig. 15: Awarded PIORs with respect to longitudinal rate limit

As expected, as the rate limit was reduced, the incipience of the vehicle configuration to RPC increased. This is shown through both the awarded HQRs and PIORs. What is apparent is that the 'triggering' of RPCs due to rate limits only occurred with the rate limit set at 2.5 deg/s. This was confirmed through the inspection of the post-processed data traces. In Fig. 15, one point exists where the pilot awarded PIOR 4 with a system rate limit of 10 deg/s. On further analysis of the data obtained during this run, it appears that no full RPC event existed; the rating was awarded due to the pilot's opinion of incipience to RPC/PIO only.

Fig. 16 displays a typical case analysed for an applied rate limit of 5 deg/s. The figure displays both the pilot-commanded and actual longitudinal swash plate deflections. It can be seen that, for very limited periods (during the capture phase of the task), rate limits are 'triggered' but there is no sustained limiting. Conversely, a trace of a severe PIO identified, shown in Fig. 17, reveals severe limiting in the period following t=30 seconds. In this case, both rate limiting and position limiting of the actuators occurs, indicative of a severe RPC event.

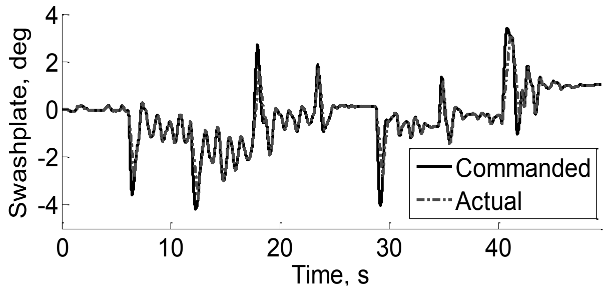

Fig. 16: Commanded and actual swash plate deflections during completion of test with 5 deg/s of longitudinal command path rate limiting, Pilot A

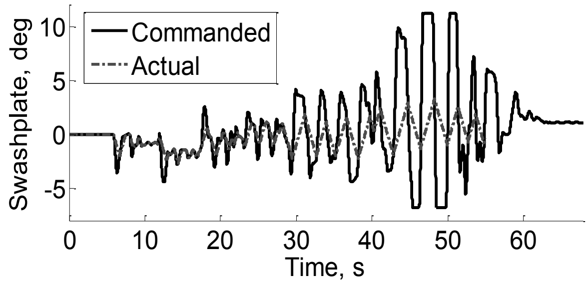

Fig. 17: Commanded and actual swash plate deflections during completion of test with 2.5 deg/s of longitudinal command path rate limiting, Pilot A

The results shown above suggest that the effects of rate limiting were apparent when set at 5 deg/s, but did not cause RPCs. Furthermore, the sustained significant triggering of rate limits at 2.5 deg/s is echoed through both the HQRs and PIORs obtained. Therefore, for the case of the pitch tracking experiment, it can be concluded that the presence of rate limiting strongly influenced the RPC susceptibility of the pilot-vehicle system.

Fig. 18 and Fig. 19 present PAC detections (obtained by using Fig. 1) with respect to HQR and PIOR ratings obtained respectively. The PAC detection cases are for the 'rated' test runs only (i.e. where subjective opinion was used to assess performance).

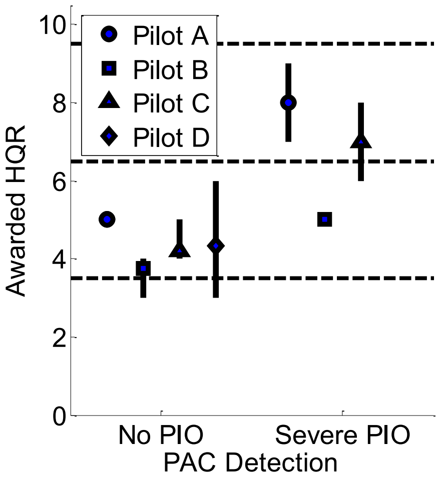

Fig. 18: Comparison between awarded HQRs and PAC detection, HFR simulator

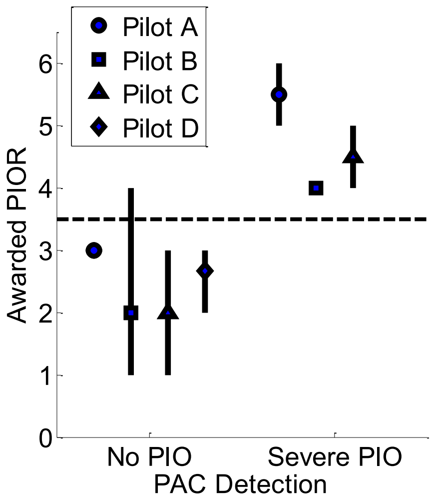

Fig. 19: Comparison between awarded PIORs and PAC detection, HFR simulator

Due to the low rate limits used to trigger RPCs in this investigation, all RPC experienced during rated runs were found to be severe events. Overall, it was found that PAC boundaries showed strong agreement with the pilot subjective opinion. This was due to a significant difference found between both HQRs and PIORs for 'no-PIO' and 'severe PIO' detections for all pilots. Referring to Fig. 5, a PIOR ≤ 3 denotes only 'undesirable motions', and not a fully developed PIO event. PIORs ≥ 4 relate to oscillations, either in closed loop control or whilst entering the control loop. As shown in Fig. 19, with the exception of one rating (awarded by Pilot B), all PIOR ≥ 4 were detected as severe PIO events. Furthermore, all PIOR ≤ 3 were detected as non events. It is worth mentioning here that Pilot D did not enter into any RPCs during the completion of the Pitch Tracking manoeuvre. On inspection of the obtained data, this was due to his almost 'open loop' control strategy throughout, whereby only a small number of control inputs were made on completion of each test point. This suggests that if the pitch tracking task is to be developed into a manoeuvre for RPC detection, modifications to the task may have to be made in order to inhibit performance of this nature (i.e. force closed loop control throughout).

Further analysis of PAC results was conducted by assessing the adequacy of prediction; whilst it is good to see correlation between subjective opinion and PAC results, the criteria must provide an onset warning of the RPC to be of any benefit. Therefore, an analysis of the detection timing was conducted.

An example of one result obtained is described using the Phase-Aggression chart shown in Fig. 20. In this case, the longitudinal rate limit was 2.5 deg/s. Markers on the figure show points where Aggression and phase difference were determined (i.e. one per second), with numbers alongside indicating the time at which they were processed.

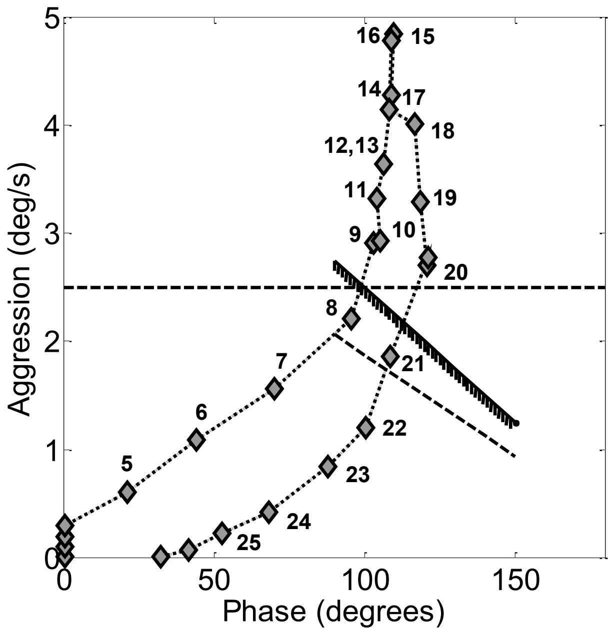

Fig. 20: Phase-Aggression Chart for completion of Pitch Tracking manoeuvre (numbers on figure relate to time-stamp of point), rate limit 2.5 deg/s

PAC enters the 'warning' region at 8 seconds, and is within the severe region before 9 seconds. Aggression remains higher than the rate limit for a further 11 seconds, and eventually the RPC event is over at a time just past 21 seconds. Fig. 21 shows the swash plate angle, vehicle rate output and pitch attitude during completion of the manoeuvre. Also shown in Fig. 21 is a shaded region representing the times identified on Fig. 20. The lighter region of shading shows the time where PAC points where found to be within the moderate PIO region, with the darker region representing the time where points were found to be within the severe region.

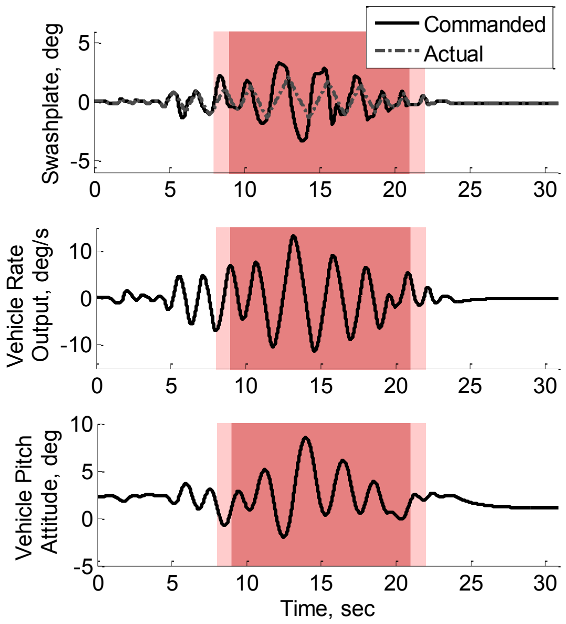

Fig. 21: Performance during completion of Pitch Tracking task with longitudinal rate limit of 2.5 deg/s

Fig. 21 shows that severe rate limiting occurs (difference between commanded and actual swash plate deflection), causing severe pitch attitudes and rates for the proportion of the manoeuvre identified using PAC boundary descriptors. Prior to PAC's detection of RPC, the vehicle experiences pitch oscillations of approximately 5 deg/s. However, up until 8 seconds, these oscillations are synchronous with pilot command, and there are no effects from the rate limiting elements. However, at 8 seconds, rate limiting serves to increase the phase difference between pilot control and vehicle rate. As the pilot acts to apply compensation to arrest the oscillations, further rate limiting occurs, causing the severe oscillations identified. It is apparent that PAC has detected the event prior to the most extreme oscillations and, as a result, its detection could have been used to either provide a warning to the pilot or initiate a system to arrest the oscillations. For example, if oscillations were arrested at 9 seconds, maximum rate excursions and pitch attitudes would have been less than 5 deg/s and 5 deg respectively. Instead, vehicle pitch rates were in excess of 10 deg/s, with pitch attitude approaching 10 deg.

To illustrate the effectiveness of PAC, the detection time was compared with the time for which the largest pitch excursions occurred for all test cases. The results are shown in Fig. 22. For all points where RPCs had been detected (9 in total), both the time of the detection and of maximum pitch excursions were obtained. The criterion was judged 'acceptable' if the detection was prior to the maximum vehicle pitch rate. This signifies that any alleviation technique would be able to identify the events prior to their maximum severity. As shown on Fig. 22, a number of detections were made significantly in advance of the maximum pitch rate occurring. These events were when RPCs occurred, and the pilot was not able to apply compensation to suppress the subsequent oscillations. It is also noted that, all of these events were the result of severe rate limiting, and divergent in nature. Those events where PAC and maximum pitch rate detection times were similar (> 1 second) were those where pilots recognised the situation, and applied adequate compensation to arrest any oscillations.

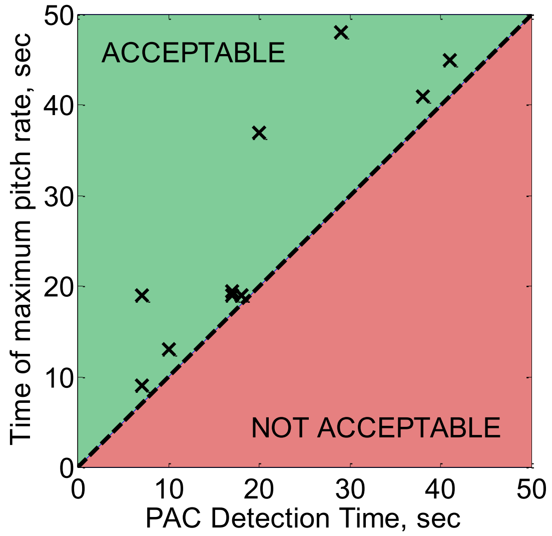

Fig. 22: Acceptability of PAC detection timing

Overall, the pitch tracking task was found to be effective at exposing RPC events due to rate limiting. Furthermore, a strong correlation between pilot subjective opinion and PAC boundary descriptors was found.

4.2 PAC Identification of Accel-Decel RPCs

All completed test points for the Accel-Decel manoeuvre were post-processed using PAC. The manoeuvre was completed in both SRS and HFR and was undertaken by three pilots (A, B and D). During the test campaign, the Accel-Decel task was used to trigger RPCs with time delays (linear events) and with rate limiting elements (quasi-linear).

Tests of the Accel-Decel manoeuvre were first performed using SRS. In these tests, predominantly time delays in the longitudinal cyclic channel only were used to trigger RPC events. Some points of interest were conducted with rate limits (5-10 deg/s), but through analysis of the obtained data, limits appeared too high and were not triggered. Overall, time delays up to 300ms appeared to have only a small effect on RPC susceptibility. For example with a time delay of 200ms, the PIOR awarded by Pilot B changed only by one point, from PIOR=1 to PIOR=2. With a 300ms time delay, PIOR=4 was awarded, but appraisal of the test data showed that the pilot appeared to enter only into small, and mild oscillations during completion of this run. This is shown in Fig. 23, alongside completions of the manoeuvre with 100ms and 200ms time delays.

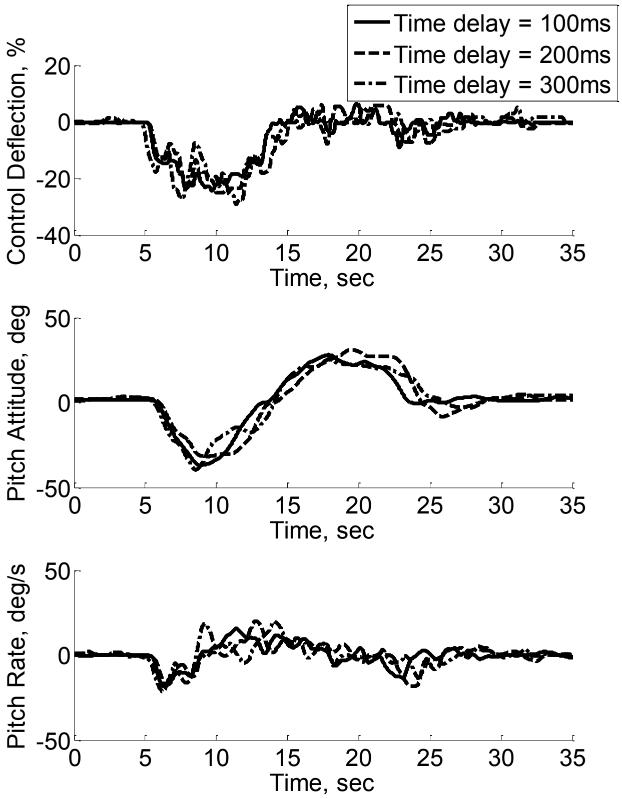

Fig. 23: Comparison of Accel-Decel manoeuvre completed with varying longitudinal cyclic time delay, SRS

Due to the concern that 'fully developed' PIOs would not be generated with time delays (that were realistic of operational rotorcraft), tests completed in HFR were conducted with time delays and rate limits in the longitudinal channel. Furthermore, these rate limits were set lower than those previously used is SRS, in order to ensure that they were triggered during the completion of the manoeuvre. In these tests, clear PIOs were found, with some causing failure to maintain task performance and, on a number of occasions, failure to maintain control. It was also found that the manoeuvre was suitable for exposing lateral RPCs (caused by rate limiting). This was seen during additional tests with Pilot D, where a combination of both lateral and longitudinal rate limits, in conjunction with time delays were used.

Fig. 24 and Fig. 25 show the HQRs and PIORs awarded with respect to the PAC detection found during post-processing. As expected, for tests completed within SRS, PAC detected no PIOs. This was in agreement with all but one of the subjective PIORs awarded. As suggested in the appraisal above, it appears only mild oscillations that did not impact on task performance resulted in the pilot awarding PIOR = 4. HQRs, shown in Fig. 24, show a perceived difference in the vehicle handling qualities for all pilots with each change in PAC detection 'level'. For example, in HFR, Pilot A awarded a mean HQR=4 where no PIO was detected, HQR=5 where moderate PIO was detected and HQR=8 when severe PIO was detected. This suggests that a change in PIO incipience is detected by both the pilot (through the change in the HQR) and by PAC (through the change in descriptor).

Results displayed in Fig. 25 also show correlation between subjective opinion and the PAC boundary descriptors. For all cases where no PIO was detected (both HFR and SRS) by PAC (17 cases), on only one occasion did a pilot award a PIOR ≥ 4. For all cases, when PAC detected some form of PIO, PIOR ≥ 3 was awarded. Furthermore, oscillations perceived as divergent were only found when PAC detected severe PIO, with each pilot identifying at least one of these cases.

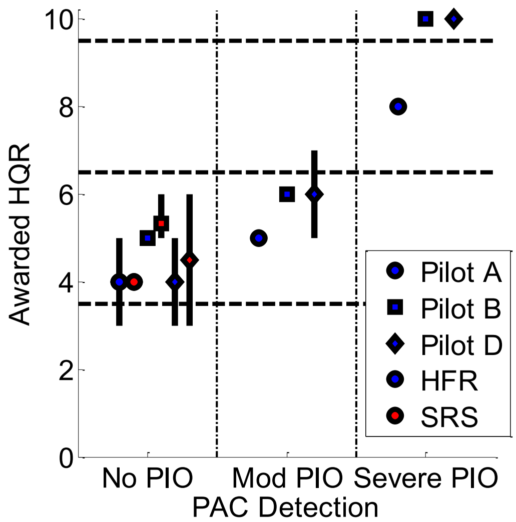

Fig. 24: Comparison between awarded HQRs and PAC detection

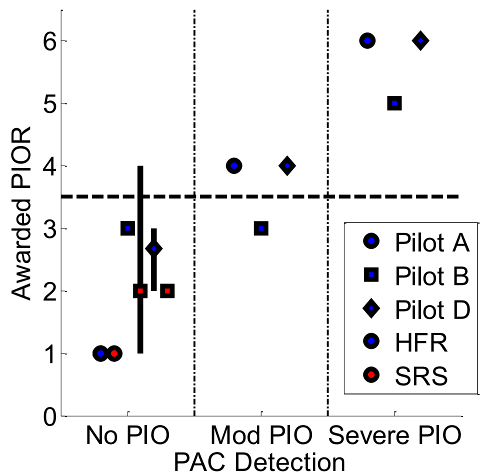

Fig. 25: Comparison between awarded PIORs and PAC detection

Fig. 26 shows an example of one such severe PIO detected by both the pilot and PAC. The shaded region shows where PAC has identified PIOs during post-processing. In this case, rate limiting is apparent from approximately 22 seconds, which causes vehicle pitch attitudes and rates of approximately 40 deg/sec and 30 deg respectively. Large attitude changes occur for approximately 17 seconds, and rate limiting ceases at 47 seconds.

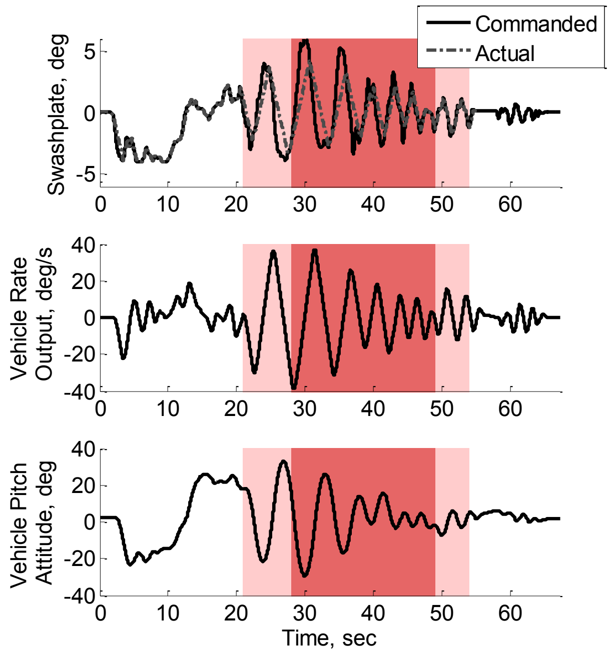

Fig. 26: Performance during completion of Accel-Decel with longitudinal rate limit of 2.5 deg/s (Pilot A)

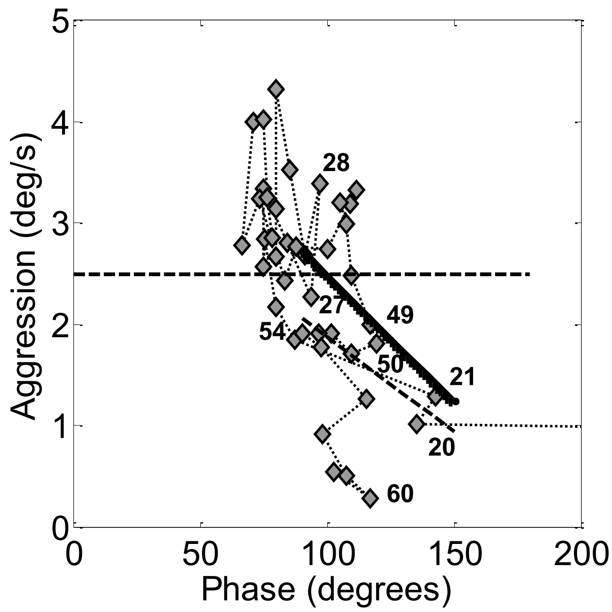

Fig. 27: Phase-Aggression Chart for completion of Accel-Decel manoeuvre (numbers on figure relate to time-stamp of point), longitudinal rate limit 2.5deg/s

Fig. 27 shows the corresponding Phase-Aggression chart for this case. Here, for clarity, only key timings are displayed on the chart. Furthermore, the chart displays only points between 20 and 60 seconds. As shown, PAC points enter the moderate region at 21 seconds, and remain in or close to the region until 27 seconds. At this point, Aggression surpasses the system rate limit, and the PAC points enter the severe PIO region. Points remain within the region until 49 seconds. Finally, data points return to the no PIO region after 54 seconds. Referring back to Fig. 26, this appears to have adequately captured the full PIO event. After 54 seconds, vehicle pitch attitude and rates are small, and the pilot is able to maintain control of the aircraft. Here, PAC has again demonstrated that it can be used to detect the event both prior to an extreme condition developing.

5. CONCLUDING REMARKS

The investigation discussed within this paper represents the first use of the Phase Aggression Criterion (PAC) since its conception as a Rotorcraft Pilot Coupling detection tool. The following have been concluded from this investigation:

1. PAC can be used to detect RPC events in multi-axis tasks in piloted simulation. This has been shown for the Accel-Decel manoeuvre, completed by three pilots in two motion-base simulators.
2. Boundaries developed in a previous investigation have been shown applicable to results presented within this paper. This suggests that boundaries are independent of the vehicle, task and operator.
3. Strong agreement was found between pilot subjective opinion and PAC boundary descriptors for both tasks presented. This was true for all pilots, in both simulation facilities used.

Overall, the results presented indicate that PAC can be used in order to recognise and alleviate RPCs in real-time. It is envisaged that this will be demonstrated in future simulation test campaigns as part of the ARISTOTEL project.

ACKNOWLEDGEMENTS

The authors wish to thank Olaf Stroosma for his assistance during the simulation trial completed in the SIMONA Research Simulator. 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., Malecki,J., DangVu,B., et al., "Present and Future Trends in Rotorcraft Pilot Couplings (RPCs) - A Retrospective Survey of Recent Research Activities within the European Project ARISTOTEL," *European Rotorcraft Forum,* ERF, Varese, Italy, 2011.

[2]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.

[3]McRuer,D. T., "Pilot-Induced Oscillations and Human Dynamic Behavior," NASA, 1995.

[4] Pavel,M. D. and Padfield,G. D., "Understanding the peculiarities of rotorcraft - Pilot - Couplings," *64th Annual Forum - AHS International, April 29, 2008 - May 1,* American Helicopter Society, Montreal, Canada, 2008.

[5] 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.

[6] 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.

[7] Blanken,C. L., Lusardi,J. A., Ivler,C. M., et al., "An investigation of rotorcraft stability-phase margin requirements in hover," *American Helicopter Society 65th Annual Forum,* American Helicopter Society Inc., Grapevine, Texas, 2009.

[8] Duda,H., "Prediction of pilot-in-the-loop oscillations due to rate saturation," *AIAA, Journal of Guidance, Control, and Dynamics,* Vol. 20,No. 3, 1997, pp. 581,581-587. doi;10.2514/2.4080

[9] 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 European Rotorcraft Forum, Liverpool, UK, 2008.

[10] Dieterich,O., Gotz,J., Dang Vu,B., et al., "Adverse Rotorcraft-Pilot Coupling: Recent Research Activities in Europe," *34th European Rotorcraft Forum,* RAeS European Rotorcraft Forum, Liverpool, UK, 2008.

[11] Mattaboni,M., Quaranta,G., Masarati,P. and Jump,M., "Experimental identification of rotorcraft pilots' biodynamic response for investigation of PAO events," *35th European Rotorcraft Forum 2009, ERF 2009, September 22, 2009 - September 25,* Deutsche Gesellschaft fuer Luft und Raumfahrt (DGLR), Hamburg, Germany, 2009.

[12] 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.

[13] Connor,R. D., "Wrecked Rotors: Understanding Rotorcraft Accidents, 1935-1945," *American Helicopter Society 66th Annual Forum,* 2010.

[14] Walden,R. B., "A Retrospective Survey of Pilot-Structural Coupling Instabilities in Naval Rotorcraft," *American Helicopter Society 63rd Annual Forum,* American Helicopter Society, 2007.

[15] Mitchell,D. G. and Klyde,D. H., "Recommended Practices for Exposing Pilot-Induced Oscillations or Tendencies in the Development Process," American Institute of Aeronautics and Astronautics, Woodland Hills, California, 2004.

[16] Mitchell,D. G., Arencibia,A. J. and Munoz,S., "Real-time detection of pilot-induced oscillations," *Collection of Technical Papers - AIAA Atmospheric Flight Mechanics Conference, August 16, 2004 - August 19,* American Institute of Aeronautics and Astronautics Inc, Providence, RI, United states, 2004.

[17] Gray III,W. R., "Boundary-avoidance tracking: A new pilot tracking model," *AIAA Atmospheric Flight Mechanics Conference 2005, August 15, 2005 - August 18,* American Institute of Aeronautics and Astronautics Inc, San Francisco, CA, United states, 2005.

[18] Gray,W. R., "Handling Qualities Evaluation at the USAF Test Pilot School," *AIAA Atmospheric Flight Mechanics Conference,* AIAA, Chicago, Illinois, 2009.

[19] Blake,R., "Boundary Avoidance Tracking: Consequences (and uses) of imposed boundaries on pilot-aircraft performance," Air Force Institute of Technology, 2009.

[20] Jones,M., Jump,M. and Lu,L., "Development of the Phase-Aggression Criterion for Rotorcraft Pilot Couplings," *Journal of Guidance, Control, and Dynamics,* (accepted for publication),

[21]Gray,W., "Boundary - Escape Tracking: A New Conception of Hazardous PIO United States Evaluation Technical Report," USAF Test Pilot School, Air Force Flight Test Center, Edwards AFB CA 93524, 2004.

[22]Anon., "Aeronautical Design Standard Performance Specification Handling Qualities Requirements for Military Rotorcraft," United States Army Aviation and Missile Command Aviation Engineering Directorate, Redstone Arsenal, Alabama, 2000.

[23]Friedmann,J., "Photomontage of a humpback whale and the DLR helicopter Bo 105," http://www.dlr.de/dlr/en/desktopdefault.aspx/tabid-10319/482_read-4684/, 2012.

[24] Anon., "Advanced Rotorcraft Technology Heliflight-R Technical Documentation," *Advanced Rotorcraft Technology,* 2007,

[25]Anon., "Heliflight: Affordable simulation for Rotorcraft Training," Advanced Rotorcraft Technology, Mountain View, California, USA, 2000.

[26] White,M. and Padfield,G. D., "The Use of Flight Simulation for Research and Teaching," *Atmospheric Flight Mechanics Conference,* 2006.

[27] Padfield,G. D. and White,M., "Flight simulation in academia HELIFLIGHT in its first year of operation at the University of Liverpool," *The Aeronautical Journal,* Vol. Sept,2003, pp. 529,529-538.

[28] Hess,R. A., "Unified theory for aircraft handling qualities and adverse aircraft-pilot coupling," *AIAA, Journal of Guidance, Control, and Dynamics,* Vol. 20,No. 6, 1997, pp. 1141,1141-1148.

[29]Ockier,C. J., "Pilot Induced Oscillations in Helicopters - Three Case Studies," Deutsche Forschungsanstalt fur Luft- und Raumfahrt, e.V (DLR), Braunschweig, 1996.

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

[31] Gouverneur,B., Mulder,J. A., van Paassen,R. and Stroosma,O., "Optimisation of the SIMONA research simulator's motion filter settings for handling qualities experiments," *AIAA Modeling and Simulation Technologies Conference and Exhibit,* 2003.

[32] White,M., Perfect,P., Padfield,G. D., Gubbels,A. W. and Berryman,A., "Progress in the development of unified fidelity metrics for rotorcraft flight simulators,", Phoenix,Arizona, 2010.

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

[34]Anon., "The SIMONA Research Simulator," http://www.lr.tudelft.nl/en/cooperation/facilities/simona/the-simona-research-simulator/, 2012.

[35] Perfect,P., White,M., Padfield,G. D., Gubbels,A. W. and Berryman,A., "Intergrating Predicted and Perceived Fidelity for Flight Simulators," *European Rotorcraft Forum 2010,* 2010.

[36]Anon., "Manual of Criteria for the Qualification of Flight Simulation Training Devices: Volume I," International Civil Aviation Organization, 2009.

[37]Sinacori,J. B., "The determination of some requirements for a helicopter flight research simulation facility," NASA, 1977.