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Aircraft and Rotorcraft Pilot Couplings – Tools and Techniques for Alleviation and Detection

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[1] **R**=Report, **P**=Prototype, **D**=Demonstrator, **O**=Other

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Executive Summary

The essential elements that interact unfavourably to create a severe A/RPC event are the pilot- the aircraft-and a triggering event. Without a trigger event (or a chain of triggering events) A/RPCs do not exist. Therefore, understanding the triggers for A/RPCs phenomena is important. The present report gives an overview on the different classes of triggers that can initiate an A/RPC (environmental, vehicle and pilot triggers).

The report show that A/RPCs can be often associated with the introduction of new designs, technologies, functions and complexities. These may introduce new triggers. New technologies such as fly-by-wire (FBW) are constantly incorporated in the aircraft. Many of these early FBW systems did have high equivalent time delays (usually as the result of input filtering) and were prone to PIOs . As a result, opportunities for A/RPCs are likely to persist or even increase, and greater attention is necessary to ensure that new technologies do not inadvertently introduce dangerous triggers, increasing the susceptibility of new aircraft/rotorcraft to A/RPC events.

The report investigated the role of simulators and flight testing in unmasking A/RPCs. Generally, one should use high-gain manoeuvres to evaluate A/RPC tendency in piloted simulations. Also, the designer should understand the relation A/RPCs and Handling qualities (HQs). Because the HQs specifications define what is desirable, meeting the handling qualities specifications provides a first level of protection against A/RPCs. Ensuring good HQs of a future aircraft is closely related to A/RPC problem.

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1. Introduction

The future design of new aerial vehicles - such as heavy rotorcraft or large transport aircraft – is related to the development of new more flexible structures. The overall flight control system must include this effect of flexibility in its design. The reason for this is that the natural frequencies of the fuselage and wing/ rotor blade structural modes decrease as their size increase, and as consequence the lower frequency structural modes have a greater influence on the vehicle dynamic response. Additionally, the weight reduction through use of composite materials contributes to the development of more flexible structures. The structural flexibility affects also the vehicle aeroelastic stability where the pilot biodynamic feedback and flight control system feedback can interact with vehicle structure, leading to pilot /control system assisted excitation of the structural modes.

These new problems illustrate a need for additional knowledge in developing models that include the interactions between the vehicle flight dynamics response, structural flexibility modes, the flight control system, and pilot biodynamic feedback in order to assess the aero-servo-elastic stability and to identify potential A/RPC oscillations.

Recalling the A/RPC definition, according to McRuer [2], there should be three simultaneous conditions met for A/RPC event:

A/RPC= Vehicle Dynamics + Trigger + Closed Loop Control

Generally, the fundamental reason for A/RPC tendency is a disagreement between the aircraft characteristics and pilot control performance. The disagreement can be a result of inadequate selection of aircraft characteristics those which play a determinant role in A/RPC mechanism. The research of methods to predict and prevent A/RPC cases should be concentrated on the study of causes, conditions and mechanisms of pilot and aircraft interactions, which can lead to A/RPC. According to the oscillation frequency spectrum, two types of A/RPC can be identified: 1) Low-frequency A/RPCs (piloting frequencies), rigid body aircraft; 2) High-frequency A/RPCs (frequency higher than piloting), rigid or elastic body aircraft.

Considering the vehicle dynamics, the main causes leading to A/RPCs are summarized in the table below.

Low frequency A/RPCs	**High frequency A/RPCs**	
	Rigid body aircraft	**Elastic body aircraft**
1) Inadequate vehicle dynamic characteristics (aircraft + control system): – High order of the system, large phase delay, low damping, and others. – Control system delay.	1) Biodynamic interaction: The biodynamic interaction in the “pilot + manipulator + aircraft” system arises due to high-frequency aircraft response to pilot activity caused by inadequate aircraft characteristics (high natural frequencies, low roll mode time constant, high control	1) Biodynamic interaction: The biodynamic interaction in the pilot-aircraft system arises due to aircraft structural elasticity and leads to involuntary manipulator

– Actuator or control surface rate limit. 2) High control sensitivity (command gain), low force-displacement gradient. *Pilot closes the loop according to the information received through visual or acceleration perception channels. APC frequencies are usually within 3-10 rad/sec.*	sensitivity, large pilot location relative to the c.g.) *The pilot closes the control loop due to aircraft accelerations acting on the body and the arm cause involuntary manipulator deflections which go to the control system and lead to high-frequency APC.* *The frequencies of these APCs usually exceed 2 Hz . Examples:Roll Ratchet, bob-weight.*	deflections transferred to control system. *The pilot closes the control loop due to structural oscillations and inertial forces acting on the body and the arm cause involuntary manipulator deflections which go to the control system and provoke high-frequency APC.*

Triggers are certain conditions or events, which force the pilot to tight control ("close the loop"). Trigger plays role of a key factor in closing the loop. The work described in this report has been guided by the goals of WP1 of ARISTOTEL [1] project and relates to acquiring an understanding of triggering events that can initiate A/RPC phenomena. The report aims to explain the influence of the triggering events and pilot perception on modeling the pilot and the vehicle dynamics. The report setup is the following: After an Introduction, Chap. 2 reviews the triggers categories showing the influence of triggering events on representative A/RPC cases. The chapter discusses also on the Category IV biodynamical couplings. Chap. 3 analyses the pilot perception mechanism with respect to vehicle motion and atmospheric illusions considered that triggering events. This review can provide information necessary to build the pilot models for A/RPC phenomena in WP2 and WP3. Chap. 4 relates to triggers that can be used to unmask A/RPCs in the simulator and Chap. 5 exemplifies some triggering conditions for flight testing. Finally, some conclusions specific to triggers for A/RPCs events end this study.

2. **Triggers definitions and categories**

The general cause of an A/RPC is commonly accepted to be due to a trigger event. The trigger causes the pilot to quickly alter his/her control strategy. The trigger can occur in a number of different situations such as wind, gust (exogenous trigger), changes in FCS mode or in aircraft functioning, discontinuities in the pilot perception or in the behavior of the vehicle, etc. (endogenous trigger) [2, 5, 27, 41, 42 and 43]. Trigger events may lead to A/RPC, however, not all trigger events will necessarily develop into A/RPC. Fig. 1 from (after Smith (ref.5) shows that A/RPCs occur because aircraft dynamics permit it. Aircraft must respond to pilots input in a manner that propagates an A/RPC.

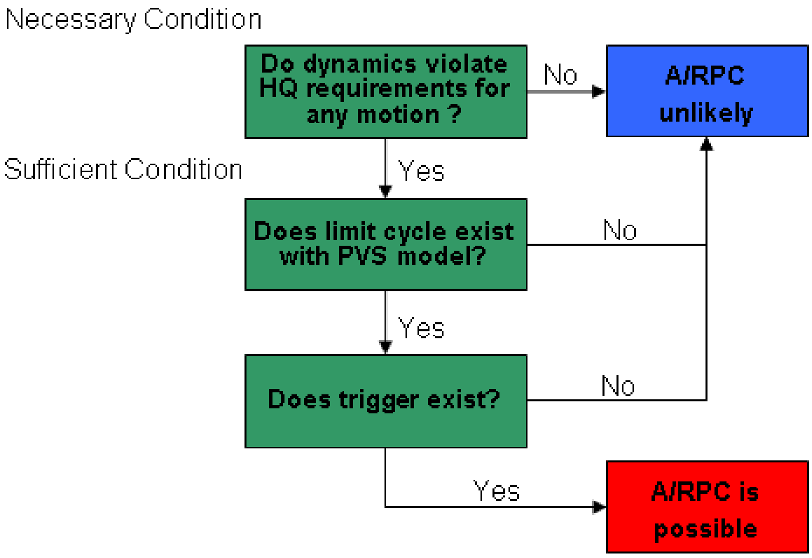


Fig. 1Conditions for A/RPC occurring (after Smith, ref.5)
PSV= pilot vehicle system

The triggers may develop under different conditions such as atmospheric turbulence, sudden change in the closed loop dynamics of the aircraft-pilot system, a nonlinear effect in flight control system, all these requiring a rapid change in pilot's control strategy. The trigger event has its effect on the pilot, but the aircraft must respond to the pilot input in a manner that propagates an A/RPC [1]. Aircraft characteristics that are known to facilitate A/RRPC behaviour include sluggish response modes, lightly damped modes, excessive phase lag or time delay, sensitive stick gradient, unusual coupling responses, and unstable modes [61-68].

Trigger definition – ***An inseparable element of A/RPC that activates a transition of vehicle motion from steady state to oscillatory or divergent motion when the pilot applies a correction control.***

There are considered three classes of triggers according to [2]: environmental triggers, vehicle triggers and pilot triggers. The environmental and pilot triggers were most frequent in the past, however, for modern configurations, vehicle triggers have become also a threat for vehicle's safety.

a) Environmental triggers

The environmental conditions can change sometimes the basic vehicle dynamics. Examples of environmental triggers are:

- Sharp wind gust, wind shear, turbulence, thunderstorm, rain or snow-blast. A wind shear associated for example with a precision landing task can force the pilot -into proper control behaviour - to induce an oscillation. The turbulence at high altitude has been joined with several A/RPC events in transport aircraft or aerial refuelling.
- Environmental conditions that change the vehicle dynamics. For example, severe icing can modify both pitch and roll characteristics.

- Other example would be a threat of imminent collision that demands a large amplitude control action, which may result in nonlinear control response.
- Other example describes one event occurred when an Air Force F4 fighter aircraft was attempting to set a low-altitude 3000 m speed record. A longitudinal PIO developed and the aircraft disintegrated due to the aerodynamic force caused by high-dynamic pressure [3].
- A sudden and large turbulence encounter can cause a pilot to actively begin high-gain, compensatory altitude tracking when previous he was only monitoring aircraft trim a making low-gain correction to vehicle attitude.
- An environmental trigger may be associated with stress of attempting what amounted to a spot landing.

b) Vehicle triggers

These triggers correspond generally to unpredictable failures of the aircraft systems (engine, control system, hydrosystem etc.) which lead to the sharp disturbance and/or the changing of aircraft handing qualities (dynamic characteristics, control sensitivity, feel system characteristics etc.). They cause changes in the effective vehicle dynamics that lead to a mismatch between the pilot control strategy and the aircraft dynamics. Three categories of vehicle dynamics triggers are distinguished:

- A Mismatch between Flight Control System and Vehicle Configurations: A usual example is a miss calibrated FCS gain or other parameter change intended to adjust the FCS properties as a function of the aircraft configurations. One significant trigger is the automatic change of the flight control system due to configuration changes (e.g. gear transition). A combination of large time delay in the FCS coupled with high gain pilot tracking activity may cause the vehicle control actuators to rate saturate or rate limit [3].

- System failures: For example, control system failures such as failure in the hydraulic system, actuator failure, uncontrolled change in aircraft trim may significant modify controllability of the vehicle. The sensor, the filter that alter the feedback dynamics to the pilot or control system may become potential triggers.

- Flight Control System Mode Shifts:
    - The potential A/RPC triggers appear through changing of the flight control laws (i.e. switch modes) to tailor the effective aircraft dynamics for different tasks. When the pilot is unaware of the mode transition, a mismatch between his mental model and the effective aircraft dynamics can appear. An example is the control law of Boeing 777 which changes between “air” mode and “ground” mode.
    - Furthermore, the transition between modes, especially in the case of failure may lead to A/RPC events. An A/RPC triggering mechanism can be developed as a result of mixed manual and automatic control modes. This is the case of elevator used manual when speed is controlled by auto throttles. More precisely, in turbulent conditions at high altitude, elevator trim motion command by stability augmentation system can interact with pilot’s manual command for pitch control.
    - Further, the nonlinear element such as rate limiter placed after the pilot’s command can introduces time lags, thereby leading the pilot to produce unreasonable inputs. It is a case of JAS39 accident which partially is attributing to this problem.

- Finally, other situation appears when a sudden takeover from automated control, such as an autopilot disconnects in out-of-trim conditions. Sometimes, the manual takeover problems have been combined with problems of mixed manual and automatic control modes. An example is TAROM A310-300 incident at Orly airport on September 24, 1994.

c) Pilot triggers

Examples to pilot triggers correspond to: aggressive pilot control to avoid the sudden collision or to follow captain or dispatcher's instruction; pilot stress due to sudden changing of flight condition; accidental or involuntary pilot actions; inaccurate piloting as a result of optical illusions, wrong piloting strategy and others.

The pilot trigger may appear after an environmental or vehicle trigger occurs, the correspondingly A/RPC event being a result of pilot overreaction or lack of appropriate reaction. The pilot's concentration on particular cues to the exclusion of others is often necessary. However, an excessive exclusive concentration can lead to a momentary excessive gain and, subsequently, a pilot trigger upset. The stress can be task-induced when the pilot attempts a high gain task as refuelling or aircraft-carrier landing. An inappropriate or incorrect control strategies adopted by the pilot can cause a pilot-triggered A/RPC. For example, the hovering task case is one when the pilot attempts to control position directly rather than indirectly through controlling altitude. Sometimes the pilot doesn't identify the appropriate control variables to accomplish a specific control task and under stress he may focus on the wrong variables. With the increasing complexity of modern FBW/FCS it may not be possible for the pilot to have an adequate mental model of the aircraft system. In unusual or emergency situations the pilot's ad hoc mental model of the aircraft FCS may lead to inappropriate control strategies and increased potential for A/RPC phenomena.

As an illustration of the pilot triggering event consider the case of American Airline Flight 587 crash AA587 [3]. During climb-out the A300-600 aircraft experienced two encounters with the wake vortices of another aircraft, a Japan Airlines Boeing 747 that had departed JFK moments earlier. When the first encounter hypothesized to be the vortex emanating from the left wing tip of JAL 747, the pilot-flying(PF) responded with significant wheel inputs (30-40 deg of wheel rotation) but with a small pedal inputs. AA587 have indicated a left turn. After approximately 15 seconds, an encounter with the second vortex occurred, this one hypothesized to be emanating from the right wing of JAL747. The cockpit accelerations that occurred in the second encounter were dominated by a vertical acceleration i. e. nose down and roll acceleration to the left. The second encounter led to large wheel and pedal inputs. The Flight Data Recorder (FDR) indicated that both wheel and pedal were moved repeatedly to the maximum positions. The FDR time histories indicated that oscillatory pilot/vehicle responses were in evidence after second encounter. The plausible triggering event established in the AA587 accident were the large cockpit lateral acceleration occurring immediately after the pilot initiated pedal inputs. It was indicated an initial maximum lateral acceleration approaching 0.5 g's (nose right), occurring about 0.2 sec after the pedal was driven to its limit (right pedal) for the first time, these correspond to large accelerations for a transport aircraft. This triggering event produced by momentum behind of the large wheel and pedal inputs has been followed by pilot flying desire to bring the aircraft to a wing level attitude after initial vertical and roll acceleration in the second wake encounter. The ground test performed on an A300-600 aircraft shows that the moving of the column, wheel and pedals in a sinusoidal fashion using full and partial displacement at 0.5 Hz frequencies closely approximate the wheel and pedal displacements of the AA587 in the last seconds of flight. Figure 2 shows the applied wheel force, resulting aileron deflection, an aileron rate when both the wheel and pedal are oscillating at a frequency of 0.5 Hz and full wheel and pedal throw are required. It is clearly that aileron actuator is under nearly constant rate saturation, this means a destabilising effect. The 0.45 sec lags due to the dynamics of both the cockpit force/feel system and actuator itself was considered very large even for an aircraft of A300-600 size. Similar though smaller delay occurred with pedal input shown in fig. 3. In conclusion, a lateral-induced oscillation (APC) was evident in the moments before the crash of AA587. The lateral directional APC oscillations were likely accompanied by similar oscillations in the longitudinal axis. The rate saturations of the aileron and rudder actuators created additional time delays in the flight control system and it required an increased wheel and pedal forces of the pilot both of which contributed to the severity and duration of APC. The sensitivity of the rudder /pedal control system of AA300-600 may constitute a control system characteristic conducive to PIO.

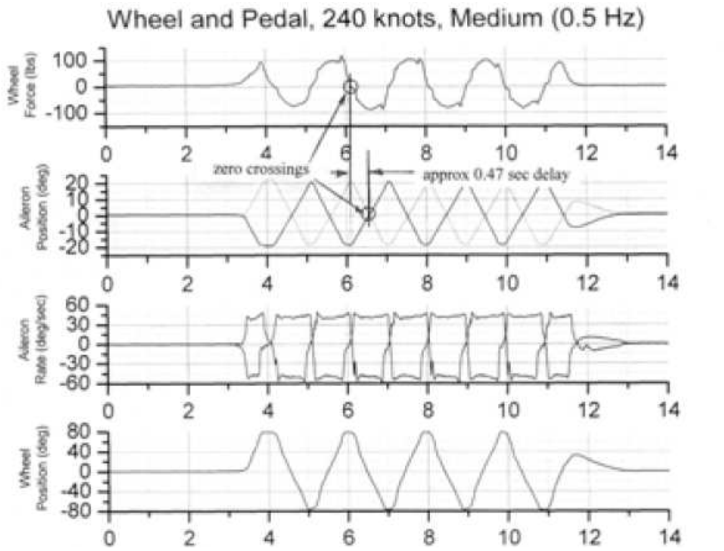


Fig. 2 A300-600 ground test results for wheel (from ref. [3])

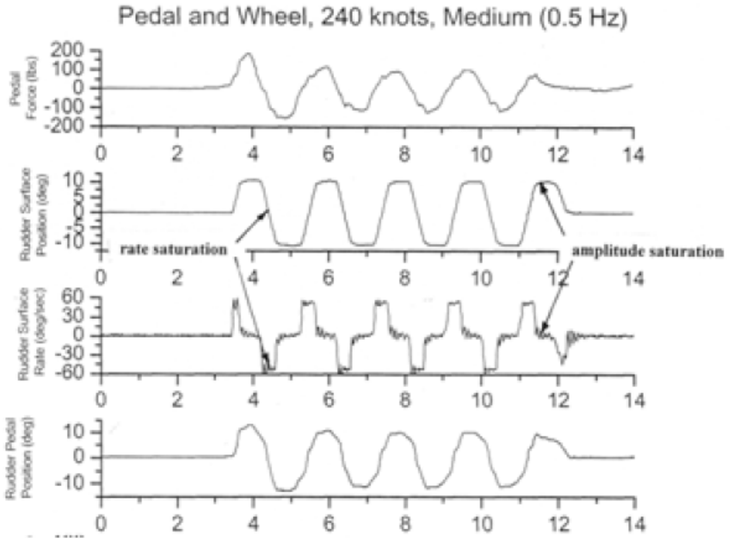


Fig. 3 A300-600 ground test results for pedal (from ref. [3])

d) <u>Non classical triggers</u>

Additionally to classical triggers other class of triggers mentioned as <u>non-classical trigger</u> can be associated with ‘abnormal’ forms of pilot dynamic behaviour. Ref.53 defines such an interaction of dynamic characteristics of the neuromuscular limb system, the aircraft dynamics and the mechanical controller with the flight control system. Generally, this initiation mechanism is associated to Category IV of A/RPC [4]. Sometimes named also as “limb-manipulator” or “limb-bob weight” effect, it tends to be the most common trigger in documented cases of rotorcraft pilot-assisted (augmented) oscillations (PAO). Generally, aeroelastic Pilot-Augmented-Oscillation are aeroelastic oscillations/mechanical vibrations that produce accelerations at the pilot station to which the pilot unintentionally couples with, sustaining or enhancing these dynamics. They correspond to unintentional closed-loop coupling and do not involve a tracking task. Following the same reference [5], a classification of aeroelastic pilot-in-the-loop oscillations is formulated as:

> Type I PAO- when the aeroelastic structural deformation produces acceleration or altitude changes at the pilot station which results in PAO when the pilot, intentionally attempts to counter these dynamics
> Type II PAO– when the aeroelastic structural deformation produces an aircraft rigid body response which results in PAO when the pilot, intentionally attempts to counter these dynamics

Because the practical limit of a normal pilot input bandwidth is about 3 Hz, a physical vibration of the pilot/stick or pilot/throttle over this limit may be taken into account.

Discussing on the triggering upsets involved in Category IV A/RPC, it is generally accepted that there are two types of passive couplings responsible for A/RPCs:

- **biomechanical coupling**: this coupling occurs when the inertial forces on the pilot and stick cause unwanted and inadvertent pilot control inputs that reinforce and sustain motion. Two categories of A/RPC events are known to correspond to the biodynamic coupling triggering [5]: 1) “roll-ratcheting” - defined as a rapid neutrally damped roll oscillation and 2) a vehicle structural modes coupling involving airframe vibrations at typically up to 4 Hz. In both cases the pilot is not consciously engaged in the close loop.
- The second type of passive coupling appears when an airframe aeroelastic mode vibrates the cockpit sufficiently to cause inadvertent pilot arm and stick inputs, resulting in control surface deflection amplifying the vehicle emotion [5].

The cockpit vibrations due to aeroelasticity can degrade the pilot ratings for two different reasons:

- vibration environment has a negative impact on comfort level or ride qualities at the pilot station
- cockpit vibrations tend to influence the precision of the pilot control inputs. This aeroelastic effect is referred to the transmission of vehicle motion from seat through pilot’s body to stick control where it produces unintended vehicle control commands as Biodynamic Feedthrough.

For helicopters, the slung load dynamics becomes important due to the much higher sensitivity to cyclic controls associated with the increased collective control needed to support the load. One of the famous RPC examples took place during operation with Navy CH-53E rotorcraft with external slung loads [ref. 53]. Here, pilot biodynamics interacted with the lower-frequency rotor dynamics, the slung load worsening the problem.

As an exemplification of the Category IV A/RPC biodynamic coupling, two case studies are given below (taken with modification from [ref. 6, 7]). To mention that all parties involved in the analysis were prepared for APC occurrence.

Case 1 considers a generic, large swept-wing, high speed aircraft with a conventional empennage. The analysis is focused on the longitudinal dynamics, using a precision tracking task. The simulation was flown by several test pilots in NASA Langley's Visual Motion Simulator. The pitch-rate-to-elevator frequency responses (rad/sec/deg) for the elastic and rigid vehicle models are shown in fig. 4.

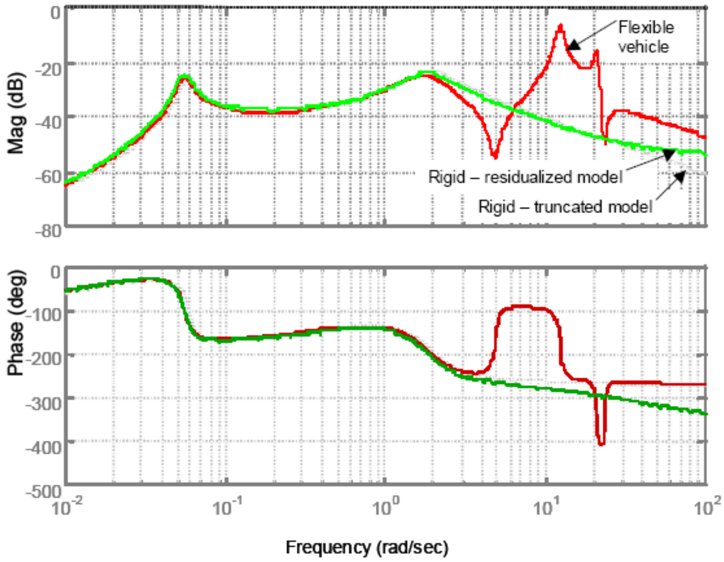


Fig. 4 Pitch rate to elevator frequency responses – flexible and rigid models (from ref. [6])

The short-period modal frequency and the first aeroelastic modal frequency both near 2 Hz are evident. A parameter in the dynamical model considered as experimental variable the in-vacuum vibration frequency of the first symmetric fuselage mode. The effect of this modal frequency on the handling characteristics is presented in fig. 5.

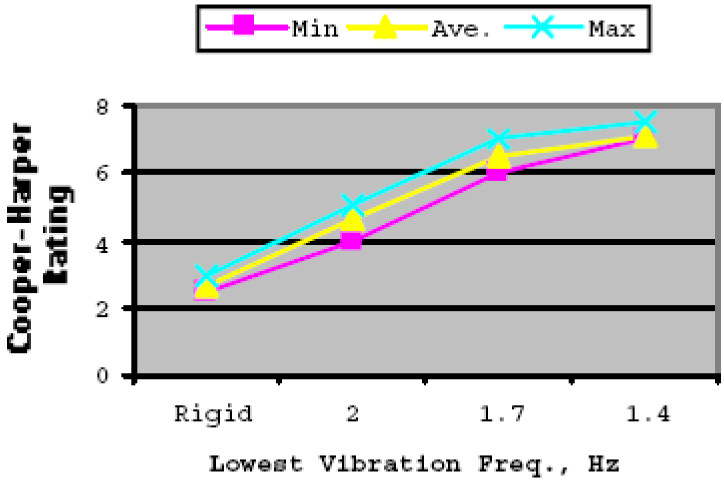


Fig. 5 Effect of increased flexibility on Handling Qualities Rating (from ref. [6])

Table 1 shows the lowest frequency of the structural vibration modes for several flight vehicles. The above case demonstrates that these frequencies can be lower than 3 Hz, in some advanced supersonic transport (AST) configurations the frequencies being as low as 1Hz. Some are well within the bandwidth of the pilot and primary flight control system and others may certain be excited by turbulence.

Table 1 Examples of lowest structural vibrations frequencies

Trends	in Elastic Frequencies
Aircraft	Frequency (rad/sec)
B1	13
Concorde	13+
C5 – A	11.
AST	≈ 6.5

Case 2 is a dynamic – aeroelastic simulation performed in NASA Langley Research Centre's Visual Motion Simulator. The aircraft in this case is an even larger high-speed aircraft than in case 1, a double-delta wing with its lowest vibration frequency around 1 Hz. The generic model includes the three lowest frequency modes in each axis, for a total of six elastic modes. The simulation results indicate that the presence of aeroelastic effect in the simulation model greatly degraded the aircraft handling qualities, especially in the lateral axis in offset landing tasks performed with and without aeroelastic effects. The Cooper Harper HQR scale is presented in table 2. Pilot comments underline that the vibrations environment had a negative impact on the ride qualities at the pilot station. The cockpit vibration tended to influence the precision of the control inputs.

Table 2 Impact of Aeroelastic effects on Handling Qualities Rating – Case study 2

Longitudinal HQRs

Pilot	A	B	C	D	E	F
ASE off	3	4	4	5	4	5
ASE on	6	7	6	7	5	6

Lateral/Directional HQRs

A	B	C	D	E	F
3	3	3	4	4	5
4	7	8	6	5	7

Other case based on the analysis of flight data presents a similarly coupling phenomenon [from ref. 8]. Fig. 6 presents an analysis of lateral offset in which the pilot is implied in the biodynamic coupling while flying the aeroelastic configurations (the frequency and time data have been normalized). The time history at the top of figure shows lateral cockpit acceleration in g's and lateral stick deflections. The plots in the lower part of fig. 5 shows the power spectral density of lateral accelerations and lateral stick deflections applied to different segments of time history. In conclusion the biodynamic coupling is evidenced by a resonant peak in the power spectral density of the pilot's stick inputs at the frequency of the one or more of the dynamic elastic modes.

All results presented in the above references suggest a biodynamic coupling and feedthrough and degradation of handling qualities [44].

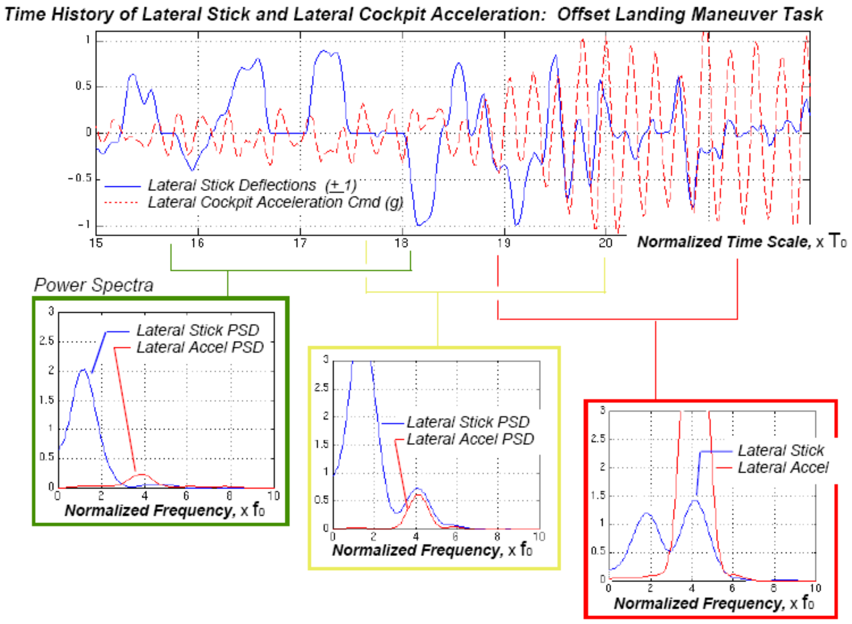


Fig. 6 Example of biodynamic coupling incident (from ref. [6])

3. Pilot visual perception and A/RPC

The human have a lot of sensors that perceives their spatial orientation [9, 10, 11]. In flying aerial vehicle the pilot self-motion, external perception and his control behaviour depend on main sensory organs which include vestibular, somatic and visual sensing and to some extent auditory sensing. At very low frequency, human motion perception is dominated by visual cues; at high frequency, motion perception depends on a variety of sources including the vestibular system and somato-sensory that responds to the motion through inertial space [12, 13]. At intermediate frequency all of these sensors can contribute significant to the perception of motion. In real world self-motion, all cues are coherent, although occasionally ambiguous.

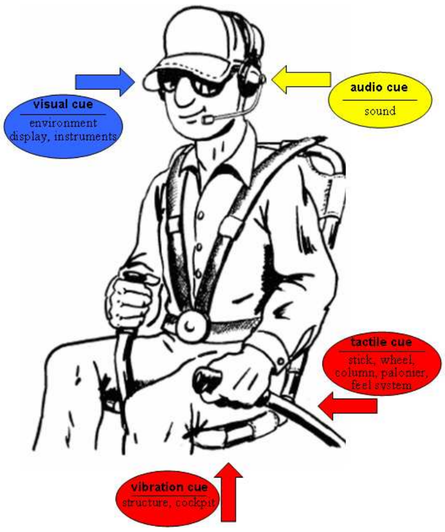


Fig. 7 Main sensory organs:
visual, vestibular, somato and audio sensing (pilot picture after ref. 69)

The vestibular organs (the semicircular canal and otholit) are sensitive to a combination of inertial acceleration and a specific force (e.g. gravity). Other important function of this organ is the stabilization of the eyes during head movement (see fig. 7). The somato-sensory system consists of tactile receptors and proprioceptive sensors. The tactile receptors are sensitive to change of force on the body (e.g. through position change). The proprioceptive sensors are sensitive to relative position of the body, also their accelerations [45, 46 and 47]. The visual perception in respect with vehicle motion is considered that the most important cues for pilot from stand point of aircraft control, close to other sensing cues (vestibular and proprioceptive).

3.1 Pilot visual perception and vehicle motion

Perception in visual cues

While flying, evolution of vehicle speed and distance to a point on the ground are crucial skills and constant demands. From the perspective of human perception these skills based on the representation in the external reference frame and the distance for pilot eyes to a target [50, 51 and 52]. The most important parameters considered in the terminal phase of aircraft motion (landing) and in rotorcraft low speed tasks (hover, landing, acceleration/deceleration, etc.), are proper depth and distance perception (also sink/vertical rate and ground speed).

Many theories in psychology’s domain offer some strategies adopted in motion perception based on ecological approach. James J. Gibson was first to study the concept of optical flow extensively in the 1950’s and became a leader in optical flow research. Optical flow regards the combined flow of all points in the visual scene. In abstract sense the optic flow is defined that the dynamic pattern of information available in the optic array along a moving trajectory of viewpoints. The optical flow theory describes the passive perception of motion and does not take into account that fact the pilot may shifts his focus of visual attention to specific target that contain some information to the task. The optical flow cannot give information about absolute distance and trajectory speed. The optical flow pattern consists of four basic components: translation, isotropic expansion (or contraction), rotation and shear, with definition in reference [15, 16 and 17].

David Lee, student of Prof. Gibson, introduced the time-to-contact concept which makes a fundamental observation that an animal’s ability to evaluate the time to pass or contact an obstacle or piece does not depend on explicit knowledge of the obstacle, its distance away or relative velocity [14]. Furthermore, professor David Lee is the leading proponent of the so-called “tau-coupling theory”. The central idea in this theory is that human and animal movement is guided by the 'time to contact or pass' a target or obstacle - a measure known as 'tau' [18, 19]. In other words, this theory proposes that moving targets are intercepted at a specified goal zone by maintaining a constant ratio between the tau (time to closure) of the gap between the hand and the goal Tau coupling plays a main role in guiding movement. Optical flow, time-to-contact and tau coupling are in motion perception theory the main concepts that provide the pilot with information about flight parameters.

When displaying the three dimensional environment onto a two dimensional display the projected pattern consists of expanding radial lines, converging in the Focus of Radial

Outflow (or Focus of Expansion) that specifies the direction of motion. Apart from Focus of Radial Outflow, optical flow theory contributes to the perception of self-motion through peripheral vision. This need foveal attention to be perceived properly, when the optical flow works in the outer area of the Field of View (FOV). FOV become important for proper determination of vehicle attitude and speed.

An overview of literature on visual motion perception shows that the main research focuses on the different tasks for both aircraft and helicopters. The optical flow theory gives some solutions in the way the pilot receive information from the environment. Using data from piloted flight simulations, the tau-guidance strategies is useful for flare and touch down manoeuvre in terms of rate of change of the tau of height above the runway surface [18,19].

The tau – guidance strategy was applied also to a helicopter in low-level flight (hover in the DVE with effects of fog) [20, 21, and 23]. Its application offers an engineering basis to the design of novel display technology. The quantification of simulator fidelity have been developed using an adaptive pilot model in acceleration/deceleration manoeuvre [23]. Based on tau-guidance strategy, reference [24] investigates the applicability of 3D prediction guidance in Synthetic Vision Display during the final phase of landing through time-to-contact and tau-coupling techniques. Reference [25] investigates change of rate of width runway angle (in respect with pilot eye) through mathematical analysis using data obtained from flight simulator landings.

Controlling an aircraft by human pilot remains a primary means of operation in case of unexpected or constantly changing missions or upon failure of parts of the automated system. Also the human pilot makes the final assessment of aircraft handling qualities [48]. The pilot will have to apply manual control, some or all tasks using visual information from the view of outside environment or the display. He continuously correct heading, height, horizontal and vertical speed in order to ensure a safe flight. The Usable Cue Environment (UCE) is an empirical method [fig.8] developed by large validation to identify the loss of visual cues when using synthetic vision system in a Degraded Visual Environment (DVE). In the DVE with the vision aids UCE is determined by rating the Visual Cue Rating for both translational and attitude. UCE that integrated part of ADS-33-PRF specification is a function of visual aid not a function of helicopter and it was developed to asses overall FOV requirements, ability to see and avoid large objects, or determine the suitability of simulator visual system [26,27].

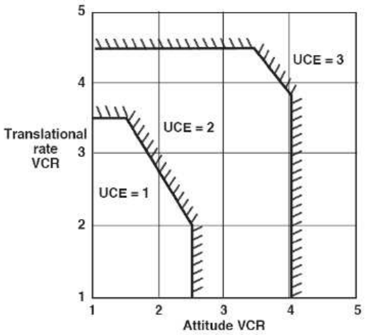


Fig. 8 UCE template (from ref. [26])

The UCE method put together handling qualities, visual perception and active control (guidance and stabilization) to provide directions for design characteristics of the control augmentation required to fly in DVE.

In different rating techniques used for handling qualities, usable cue environment (helicopters) and A/RPC susceptibility described above are typically used empirically. During simulations or flight tests values of the rating techniques are determined as a function of control system configurations or other independent variables. An exploratory analysis shows that tau-coupling technique offers a robust approach to the design of a synthetic vision system in extending UCE scale [23].

Optical Illusion as triggering events

Optical illusion was categorized in the beginning of this study as corresponding to pilot trigger. Practically every visual cue may be susceptible to illusion stimuli acting as triggering events. Several general publications resulted from Flight Safety Foundation's Approach-and-Landing Accident Reduction (ACAR) Task Force [15] indicate the pilots should be aware of visual illusion in landing and give some advice to decrease the crew's vulnerability. Sometimes these reports are purely intended for pilots and do not offer a scientific approach to the perceptual questions. An overview of the illusion is presented as follows:

- runway width illusion appear when landing on a narrower (wider) runway than the pilot is used. In such case the pilot is likely to fly a lower (higher) approach as he developed a mental model where altitude is coupled to the apparent with of the normal runway. The apparent runway width is an important cue for maintain a proper glide path. This is result of theoretical study which perform that the runway with illusion may have dramatic consequences
- sloping runway/terrain illusion – when the runway is up (down) sloping, the pilot should follow a shallower (steeper) approach path. If the pilot is not aware of the slope he will interpret the different runway perspective cues as flying at too high (low) – if maintain the same glide path – will land/crash short of the runway (overshoot runway)
- (un)familiar size illusion – occurs when pilot estimates his altitude or distance based on the apparent size of 'familiar object' which in reality have a different size than the ones the pilot is familiar with
- black hole illusion – this term for spatial disorientation during night approaches is due to limited optical flow and familiar size cues and the absence of horizon information. This illusion lead to a misperception of altitude or distance
- false horizon illusion – appear when distant mountains obscure the true horizon or when a shoreline is more or parallel to the true horizon
- atmospheric illusion – an unusual atmospheric conditions can create several illusions that water refraction that influence perceived distance to runway and additionally give the impression of being too high. Other example is that brighter runway lights or cleaner (no polluted) air than usual give the illusion that the airport is very near. Entering a fog layer can create the illusion of pitch up that mean the pilot will suddenly steeper the approach

The atmospheric illusions (low visibility conditions) are considered that occasionally triggering events for A/RPC phenomena and may lead to a missadaptation of the pilot. These are considered a major source of upsets that surrounding external environment and include changes in the pilot's attention which reflected into higher pilot workload.

4. Specific triggers and conditions proposed to be used in flight simulator campaign

Ground Based Simulators have the advantage of being:

1) Readily available at design site and
2) Playing a key role in developmental evolution of dynamic elements.

However, they have main limitations:

1) Fidelity of synthetic visual and motion cues (worst in conditions where many current FCS problems erupt)
2) Task environment, i.e. the control strategy (can be quite different from flight) an
3) Lack of real flight stress.

Parrag[70], affirms that "*History indicates that for demanding highgain tasks, ground based simulation has often been misleading - failed to expose dangerous problems*". Mitchell and Klyde [71] summarize their conclusion on simulators's use for A/RPCs as following: "*It is often stated that ground simulation is notoriously poor as a tool for exposing PIO prior to flight. This statement is actually not provable or disprovable, except anecdotally. To the authors' knowledge, aircraft development programs do not routinely document the discovery of PIO susceptibility in early simulation, identify and fix the cause, and then perform extensive flight testing to verify that the problem is really fixed. We hear only about the opposite: PIOs that occur in flight and were not expected based on simulation testing. When PIO occurs in flight, then, simulation is one aspect of the development process that will undergo intense scrutiny: why didn't the problem show up in the simulator? what could have been done to expose the PIO? is the simulation model even accurate enough to trust? etc."*

The question is then: "Is ground-based simulation useful to unmask A/RPCs?",To answer this question one has to think that, in the future, simulators are going to be used more and more in the design process. Therefore, denying their role in unmasking A/RPCs would be a mistake for future design. McRuers's committee [2] comments on the same question that: "*Even with the continuing development of analytical criteria to predict and prevent both linear and nonlinear PIOs, ground simulation will always be considered an indispensable tool in the development of any new aircraft design. As such – and with the trend toward shrinking money for flight testing, for the foreseeable future – simulation will be used increasingly to investigate PIO. Capabilities for visual and motion systems in simulators continue to evolve. Unfortunately, no matter how far this evolution goes, it will never completely replicate the real world. So some level of doubt will exist about the ability of ground simulation to supplant actual flying, especially when investigating a random, sporadic event like PIO... The unfortunate truth is that, no matter how much ground simulation evolves, it will never take the place of real flight testing. Ground simulation is a risk mitigation tool, not a risk elimination method.*"

The present chapter tries to answer to the critical questions regarding fixed-based simulators: Is ground-based simulation useful? How to test for A/RPCs? What tasks should be flown, and how? When do we know we have finished the testing? The present chapter is intended to give some guidelines to the reader on how and what should be tested in the simulator for verifying the existence/ non-existance of A/RPCs. Good investigations related to this question belong for APCs to McRuer [2], Schroeder et al.[73], Kish et al. [73],Mitchell and Stadler [74] and Mitchell and Klyde [71], Wasei et. Al. [75] and for rotorcraft to GARTEUR AG-16 [76].

Mitchell and Klyde [71] identify five challenges to be fullfilled in order to trust A/RPCs simulator tests. These are:

1. Adequacy of the Math Model

The challenges for providing an adequate mathematical model are immense. Reference # is quite negative on this matter, stating that *“when the model is based on computational methods, hopefully augmented with data from wind tunnel tests, there is little hope of adequately accounting for all of the elements that contribute to PIO, whether linear or nonlinear in nature. Before actuators and augmentation systems are included, even the simplest of analytical methods – such as classical requirements on short-period damping and frequency – should suffice to identify the potential for poor flying qualities, and hence the likelihood for PIO. And for modern, relaxed-static-stability aircraft in particular, identification of PIO tendencies for such simple models does not mean much to the flight controls engineer; the need for stability augmentation will have been acknowledged long before this point. Even after flight testing begins, the challenges for providing an adequate math model are imposing. Initial flight testing is centered on basic flight clearance and envelope expansion, not on generation of test inputs suitable for math model development. The types of data needed by the simulation engineer are not likely to be available for months, perhaps years. The best one might hope for are gross adjustments to stability derivatives or control power estimates, and these will be in relatively low-risk flight regions where PIO is not likely to occur anyway.*”

2. Simulation Artifacts

Simulators introduce their own artifacts that complicate the issue of identifying PIO tendencies. The most wellknown of the artifacts are the additional latencies resulting from the visual and motion systems and computation of the math model; uncorrelated responses from limited-travel motion systems; and loss of visual acuity from the visual scene. The most critical artifact of ground simulation is the lack of realism in the “out-the-window view”, this is true especially for helicopters. Also, it is difficult to replicate the stress level resulting from impending impact with a real runway, with real-world gusts and wind shears. Attempts to introduce artificial changes in the simulation to account for this lack of realism have not been successful according to Michell and Klyde [71].

Mitchel and Klyde [71] give the example of the assessment of potential for Category II A/RPC. Such an assessment requires as complete a model of the actuator dynamics as possible. In the past, actuator dynamics have been handled in one of two ways:

1) Ignore the actuator dynamics entirely, assuming the delays resulting from the actuator are approximated by the update rates of the math model and visual systems. The impact on handling qualities of time delay – whether it is pure delay from computers or the equivalent delay from a servohydraulic actuation system – is well known. Unfortunately, if the goal is to assess A/RPC potential, this assumption is not reasonable.
2) Represent the lags of the actuators by a low-order transfer function, typically no larger than second order. This method at least replicates the initial response of a servohydraulic system but it does not account for the inherent acceleration, rate, and position limiters that are factors in Category II PIO. Most modern augmented aircraft use software rate limiters upstream of the hardware commands, specifically to avoid reaching the rate limits of the

surface actuators. When software rate limiters are included, in the proper locations and with the proper limits, the importance of using accurate models of the hardware is lessened. Simulation is an ideal place to verify that the software rate limiters function as intended. Unfortunately, the combination of computational delays and an accurate actuator model results in a cascading of time delay elements that will result in larger throughput delays than in the actual aircraft.

3. Pilot acceptance

"A challenge for the engineer is to gain the confidence of experimental test pilots that the simulation is a faithful replication of the airplane and should, therefore, be taken entirely seriously. Experienced pilots are unfortunately accustomed to flying simulators that are fundamentally different from the aircraft in cockpit layout, control feel system characteristics, and basic response dynamics. To ask the same pilots to look for evidence of PIO is sometimes a stretch. This is not a question of the integrity of test pilots; rather, it is a criticism of the state of piloted simulation as experienced by today's test pilots. When a simulation model simply does not respond in a way the pilot expects – even if the error is something as innocuous as a trim difference, or an incorrect mode transition in the flight control system – any hint of realism can be lost. It is too easy to press a reset button in the cockpit and endany hope of exposing a real event. A well-documented source of pilot skepticism is in the overall aircraft response in the simulator. Pilots with considerable experience in a certain aircraft are likely to complain that the simulator seems too sluggish in its initial response."[71]

4. Perception of PIO

Accordinbg to [71], there is evidence that, even when A/RPC is experienced in a simulator, the pilot may not be aware of it or may, at worst, perceive it to be more mild than it might be in flight. It is not always possible for the pilot to perceive PIO in a simulator – not because the pilot doesn't want to, but because the cues are not adequate.

Further, Parrag [70] underlines that piloting population is not uniform: There are low gain predictive types and there are high gain "ham fisted" types. Both types need to be covered in A/RPC search, but especially latter. The tests should also include both: Pilots unfamiliar with particular aircraft being tested, their unbiased first opinions can be very telling and also Test pilots who have experienced PIOs in past and who can effectively communicate their evaluations.

There is a burden expected of the experienced engineer, to work with the pilot in testing for A/RPC, and to note occurrences in aircraft controls and states that are indicative of A/RPC even if the pilot does not see it. This requires the engineer be knowledgeable of the signs of A/RPC. If such an event is identified, the pilot should be asked to repeat the evaluation and look for signs of A/RPC, perhaps even with more abusive control inputs to aggravate the condition.

5. Identifying the Right PIO

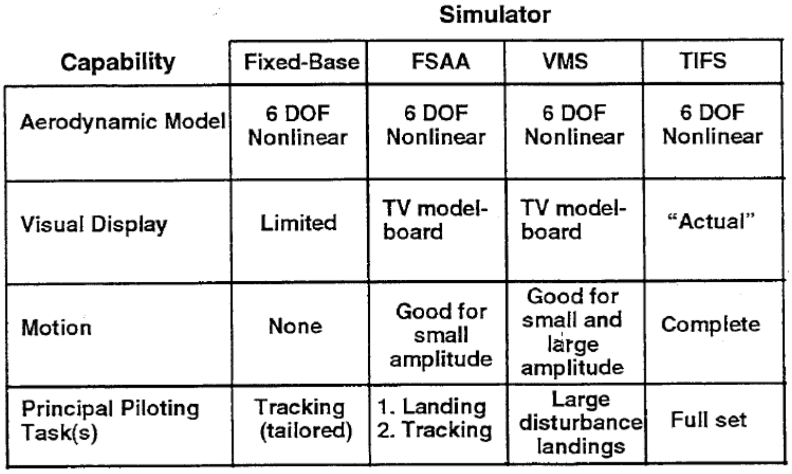
Even when PIO is exposed in a simulator, there is always a question of whether the event is real. If the goal of the simulation is to replicate an event that has already occurred, it should be possible to identify similar causes and similar response characteristics. For example, if a particular design is known to exhibit roll PIOs on landing as a result of aileron rate limiting, simulation replications should closely reproduce the frequency and amplitude of the flight event. Because of the lack of perception of the event in the simulator, it is entirely possible that the PIO in the simulator will be of considerably larger amplitude (before it can be perceived) and lower frequency (because of higher time delays/latencies and more extensive *rate limiting) than the flight event. A PIO that is of lower amplitude and higher frequency in the simulator probably is not a faithful replication of the flight event. The more likely scenario, of course, is that a flight event will never be accurately replicated in the simulator.* [71]

Fixed-based or motion-based simulation to unmask A/RPCs?

Many experts question especially the use of **fixed-based simulation** to discover and eliminate adverse A/RPC tendencies. For example, McRuer's committee [2] is convinced that "*properly configured fixed-base simulations can be reliable indicators of many potential adverse APC tendencies*". For RPCs, the use of fixed-base simulator is even more questionable than in the case of APC testing.

As concerns moving-base simulators, as they have the capability of emulgating motion, at least to a limited extent, they would appear to be more powerful tolls for assessing A/RPCs susceptibility than fixed-based simulators. However, the utility of these simulators has also been called into question. McRuer compares a group of four simulators used in NASA's investigation on the shuttle PIO incidence (see Table 3 from ref. 2)

Table 3 A comparison of NASA and US Air Force simulators for principal piloting tasks, circa 1975 [ref. 2], pp. 113



	Simulator			
Capability	Fixed-Base	FSAA	VMS	TIFS
Aerodynamic Model	6 DOF Nonlinear	6 DOF Nonlinear	6 DOF Nonlinear	6 DOF Nonlinear
Visual Display	Limited	TV model-board	TV model-board	"Actual"
Motion	None	Good for small amplitude	Good for small and large amplitude	Complete
Principal Piloting Task(s)	Tracking (tailored)	1. Landing 2. Tracking	Large disturbance landings	Full set

The Simulator for Advanced Aircraft (FSAA) was a moving-base simulator capable of large lateral translations. The Vertical Motion Simulaotr (VMS) is capable of large vertical translations. The Total-In Flight Simulator (TIFS) is a higly modified C-131 transport.

How to test for A/RPCs in the simulator?

Regarding the question "How to test for A/RPCs?" probably the best procedure is to start by testing first Category I A/RPC (essentially Linear Pilot-Vehicle System Oscillations). Usually, cat I A/RPCs can be well understood in the simulator tests. Then one should test in the simulator for Category II A/RPCs (i.e. Quasi-Linear Pilot-Vehicle System Oscillations with Surface Rate or Position Limiting). These are the most common true limit-cycle severe A/RPC. They are severe, with oscillation amplitudes well into the range where actuator rate and/or position limiting in series with the pilot are present as primary nonlinearities. To test for these PIOs in the simulator one should be able to reproduce accurately the actuator dynamics in the simulator. For example, on the space shuttle orbiter PIO in 1977, the

Category II PIOs encountered there could be associated with the presence of excessive effective time delays in the effective aircraft dynamics coupled with a severe flight scenario, for example, first landing on a runway and no power available for go-around, that triggered very high-gain closed-loop piloting. These phenomena, including the impact of delays due to actuator rate limiting, can be also understood in the simulator tests. Testing for Category IIIPIO s (i.e "Essentially Non-Linear Pilot-Vehicle System Oscillations with Transitions) can be much more complicated to analyze than the other two in that they that they intrinsically involve transitions in either the pilot or the effective controlled element dynamics.") it is a challenge in itself to be done in the simulator as the mathematical model, the visuals and motion characteristics must replicate the truth aircraft.

An example of a detailed procedure for testing Cat I ans Cat.II PIOs in the simulator is given by the so-called "HAVE PIO" truth model experiment and "HAVE LIMITS" experiment. The idea of HAVE PIO was that, for reproducing in-flight A/RPCs in the simulator, one should use a set of flight data, during which A/RPCs were encountered, these data being used as a "truth model". Therefore, APCs were induced in-flight by three USAF test pilots in the variable-stability NT-33A aircraft, a two-place airplane with a safety pilot capable of taking over manual control at any time. While HAVE PIO was meant to focuse entirely on Category I (linear) events; HAVE LIMITS applied to more severe APCs, characteristic for Category II APC. For HAVE PIO eighteen pitch configurations were evaluated in flight in the offset approach/precision landing task. Variations in short-period frequency and added lag filters produced airplanes that ranged in flying qualities from excellent to highly PIO-prone. For HAVE LIMITS, Category II PIOs were induced by combinations of lag filters and software rate limiters in the pitch axis. A step-and-ramp tracking task was used for all evaluations on the variable-stability NT-33 airplane. After performing the flights, simulator experiments were built up with the goal to replicate the conditions of HAVE PIO and HAVE LIMITS (this includes dynamic models of the airplane and the visual runway environment, on ground-based simulators and then measure their effectiveness at reproducing the pilot ratings of the "truth model."). The main conclusion of this exercise were: The primary metrics for measuring the effectiveness of simulator w.r.t. flight were the subjective pilot ratings, Cooper-Harper Handling Qualities Rating (HQR) and PIO Tendency Rating (PIOR). The closer the ratings to the "truth model," the more effective the simulators would be judged. "*Despite the apparent failings of simulation to replicate the flight results of HAVE PIO, and despite the differences in ratings from the HAVE LIMITS comparisons, there is still some promise in the data.*" [71]: The following main observations were made [71]:

- If a particular configuration is bad (mean HQR worse than 6.5 and PIOR of 4 or worse) in the simulator it will be even worse in flight. If it is moderately good (mean HQR 4 or better and PIOR better than 3) in the simulator it may be even better in flight. No real conclusions can be made about configurations between these extremes, as they may be either better, worse, or the same in flight.
- Insight can be gained by looking at quantitative data (time histories) from the simulator and comparing these data with known in-flight PIOs. Generally, it is expected that the simulation events will be much more severe, but that the pilots may not be aware of this.
- A large pilot population must be used, and it appears to be more important in the simulator than in flight. Both of HAVE PIO simulations used five pilots, and in both cases at least one of the pilots failed to see PIO for most of the PIO-prone configurations. The HAVE LIMITS simulation used as many as nine pilots, and in some cases at least one pilot failed to see PIO, even if the airplane were highly susceptible to explosive, unrecoverable, divergent PIO. Five would seem to be a minimum pilot population; if it were possible to select the specific subjects, a smaller

number could be used, as long as more than one of the pilots has proven capable of identifying PIOs in a simulator.

- It is imperative that all pilots receive a thorough briefing on the use of the PIO Tendency Rating Scale, and that all understand what constitutes full-blown PIO as opposed to nuisance “bobbles” with respect to the assignment of PIORs.
- Ratings from the PIO Tendency Rating Scale must always be interpreted in conjunction with Handling Qualities Ratings and are not to be considered stand-alone ratings.

There are some limited experiences with attempts to replicate real-world PIOs in the simulator after they have occurred in flight. Mitchell and Klyde [71] consider that “*We can learn something about the steps required after PIO has occurred, and hopefully adopt the same steps before one occurs on a future aircraft.”* They give three famous examples for this:

- YF-22 Experience: Following the 1992 PIO of the YF-22,16 the U.S. Air Force and Lockheed Martin initiated extensive studies to identify the cause, improve the control laws, and develop a systematic process for design. Simulation was an integral part of the process. While it has not been reported whether engineers were ever able to precisely replicate the Edwards AFB event, we do know that they developed a series of high-gain tracking tasks to force highbandwidth pilot-in-the-loop activity.

- NASA F/A-18 HARV Experience: In 1994, during high-angle-of-attack flight testing, the NASA F/A-18 High Alpha Research Vehicle (HARV) experienced a longitudinal PIO.18 This PIO had not been exposed in simulation prior to the flight testing. In postflight simulations, modifications were required to the standard maneuvers to replicate the PIO. These modifications were then adopted for future simulation testing prior to flight testing of new control laws designs. The standard evaluation task involved tracking another airplane while in high-angle-of-attack flight. Modifications consisted of 1) changing the task from a conventional tracking exercise to a combat exercise, in which a “kill” was to be achieved; and 2) changing the target aircraft’s longitudinal position in random-looking steps. This stepping-target tracking task was shown to be an effective simulation technique for reducing PIO potential during control system design.

- MV-22 Osprey Experience: A Marine Corps MV-22 tiltrotor aircraft experienced a roll PIO in a landing attempt on a ship deck during sea trials in February 1999. Simulation testing had not exposed the PIO tendency before the event, and after the event, initial attempts to replicate the condition were not successful. Several changes to the simulation were required to consistently reproduce the PIO. First, artificial visual cues (hover ladders) were added to the visual scene to increase pilot gain. Second, changes to the ship airwake environment were required to approximate the conditions recorded during the flight event. With these changes, the PIO could be repeated fairly easily, and fixes to the control laws could be flown and evaluated prior to return to the ship. 10. C-17A Experience The C-17 cargo airplane experienced several PIOs during its full-scale development program.3 The PIOs stopped occurring until 2001, when the aircraft joined Operation Enduring Freedom in Afghanistan, Boeing engineers used a series of both high-pilot-gain and large-amplitude tasks to evaluate changes to the control laws to minimize the potential for PIO.

An example of tests performed in the simulator for unmasking RPCs cat. I and II is given during GARTEUR AG-16. There pilot-in-the-loop investigation into rotorcraft-pilot coupling were presented for three test campaigns corresponding to rigid body A/RPCs; biodynamic A/RPCs and aeroelastic A/RPCs.

Regarding the rigid-body RPCs tested during GARTEUR AG-16, these manoeuvres were selected to ensure that the pilot undertook some control task/activity in each of the vehicle axes with the intention that this activity might drive the pilot-vehicle system into an RPC event. The tasks performed were (in no particular order): 1) Vertical manoeuvre (with external gust disturbances present). 2) Roll command tracking task (no gust disturbances present).3)Slalom pole course (no gust disturbances present). 4) Lateral side-step task (no gust disturbances present). 5) Boundary avoidance tracking task (no gust disturbances present). Two pilots were available for the research project and each pilot flew the courses at least twice.

5. APC/PIO triggers conditions encountered during flight tests and operational incidents cases, the base for A/RPC evaluation campaigns

The A/RPC flight test process has as objective is to minimize risk of A/RPC occurrence in operational use, or in other words to find the "black holes" that one can trigger later in operational use of the aircraft. Flight testing for A/RPCs has the following advantages with respect to ground-based A/RPC simulations:

1) the visual and motion cue environment are correct as they are real, they are not synthetic like in the simulators;
2) there is a real flight stress and
3) there is a real piloting task.

However, flight testing is a very costly tool and a high risk environment for testing potentially questionable or unknown characteristics of the aircraft or very dangerous manoeuvres.

For flight testing, one should keep in mind that there are several important aspects for triggering the A/RPC phenomenon, i.e.:

- The variety of pilot input-aircraft response features that cause unpredictability is a root causal factor in A/RPCs
- The pilot's way to characterize a A/RPC in terms of how it *affects* the piloting task
- The circumstances that may trigger A/RPC events.

Only by understanding the above factors when structuring the flight test methodology oriented at uncovering A/RPCs susceptibility will guarantee the testing success. Also, the clever introduction of "bigger events" to reproduce surprise and stress may lead to a successful flight test for A/RPCs as it forces "unusual control inputs".

Parrag [70] divides the flight test tasks for A/RPCs into two categories: real tasks and synthetic tasks. Generally, flight test tasks must be tested against known problem configurations and consistently expose potential or latent "black holes". Flight test tasks must generally indicate "good" aircraft to indeed be good

Real tasks are characterized use no special displays and involve a single element or a combination of elements from an operational scenario. Examples of such real tasks are: . pitch or roll attitude captures; 45° bank level (c onst. altitude) turns with aggressive reversal; close formation flight; Air to Air Tracking; probe and drogue refueling task; offset landing approaches; aggressive alternate tracking of runway edge @ 100 ft above ground level (or altitude safely appropriate for particular aircraft size)). Synthetic tasks correspond to:

Tracking task presented on a convenient pilot display (such as: HUD (Head Up Display), MFD (Multi Function Display); Attitude Director Bars) or presented on a removable LCD display with tasks preprogrammed on a PC. computer (demonstrated in Learjet).

The primary objective of synthetic tasks is to expose PIO/dangerous overcontrol potential and minimize risks of occurrence once aircraft is "certified". Hence, one needs to force test input sequences that stress the pilot-vehicle system to extremes even if unrealistic from an operator standpoint (e.g."klunk" inputs used by Saab). Generally, synthetic tasks must include single axis and combined axes elements with sufficient frequency and amplitude content on the tracking bar to test for A/RPC susceptibility with both single axis and coupled inputs. For the synthetic tasks one needs to brief pilot to aggressively work to keep errors zero. Synthetic tasks correspond for example to high gain - aggressive closed loop behavior (therefore, it works on high frequency portion of pilot - vehicle transfer characteristics) or for example to high frequency tasks (quick or sharp initial response) - this is region where problematic (cliffy) phase lags, phase rates and rate saturation effects occur. Synthetic tasks should be programmed to occasionally require inputs from pilot that may seem operationally unrealistic (e.g. rapid, full throw inputs).

There are two types of synthetic tasks known during flight testing [70]:

1) Discrete Tracking Task (DTT) as for example:
   -combination of steps, ramps in both pitch and roll but "coordinated"
   -can separately control amplitude of pitch and roll separately to match task to nature of aircraft being tested
   -objective is to elicit both gross acquisition and fine tracking activity
2) Sum of sines such as:
   -combination of sine waves of different frequencies
   -1st or 2nd order frequency roll off (filter)
   -pitch and roll amplitudes separately controllable again to match task to aircraft being tested
   -objective is to elicit aggressive line tracking activity

According to ref. [#], A/RPCs have two distinguishing features namely, frequency and amplitude, that determine how the pilot can deal with PIO in context of a task. Examples are here:

1) High frequency, low amplitude tasks. An example is the roll ratcheting task characterized by excessive rolls which cause rapid reversals by pilot. Such task settles into "dominant cue/synchronous behavior". It is viewed by pilot as very annoying but task remains controllable. The pilot can easily judge average of PIO's.
2) Low frequency, larger amplitude tasks. Such tasks are often seen with rate limiting. The pilot is unable to judge average of oscillations. The task is generally not controllable if task constraints do not permit pilot to back out
3) Medium frequency tasks. Such tasks are seen as a gray area for A/RPC analysis. The degree of problem caused in task depends on the amplitude of PIO; on how much the pilot is "driven" by a dominant cue; on whether pilot can manipulate "average" to continue task nad on the personal piloting technique (i.e. can pilot tone down his inputs?)

One needs to think both to frequency and amplitude of the A/RPC events when designing the flight tasks.

For flight test tasks one needs unique instrumentation requirements for A/RPC recognision:

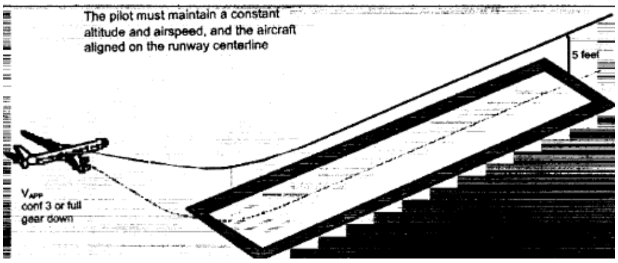
1) During Flight Test: Data sampling rates 30 hz or higher for rigid body pilot vehichle system dynamics (i.e. fast variables); Lower data rates for slow variables such as altitude airspeed; Should get derivative of aircraft rotational rates and perhaps even

2nd derivative ("jerk" motions); Instrument for nzp, nyp; Should instrument for actuator rates and control margins;

2) In Operational Use: Flight Data Recorder; Sufficient data channels to record critical variable; -Sampling rates for critical parameters need to be at least 15-20 Hz.

Airbus [ref 77] gives examples of synthetic and non-synthetic manoeuvres for unmasking APC. If APC is equivalent to Pilot High Gain, it follows that the designer has to take care of: 1) unexperieced pilots; 2) stressful environment (final approach, formation flight, workload) and 3) capture and fine tracks (altitude, heading, speed, roll, yaw).As systematic manoeuvres, Airbus executes (see Fig. 9)

the Runway Fly Over Manoeuvre.



Low altitude aggressive manoeuvres

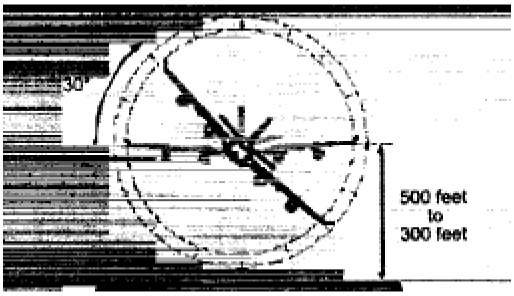
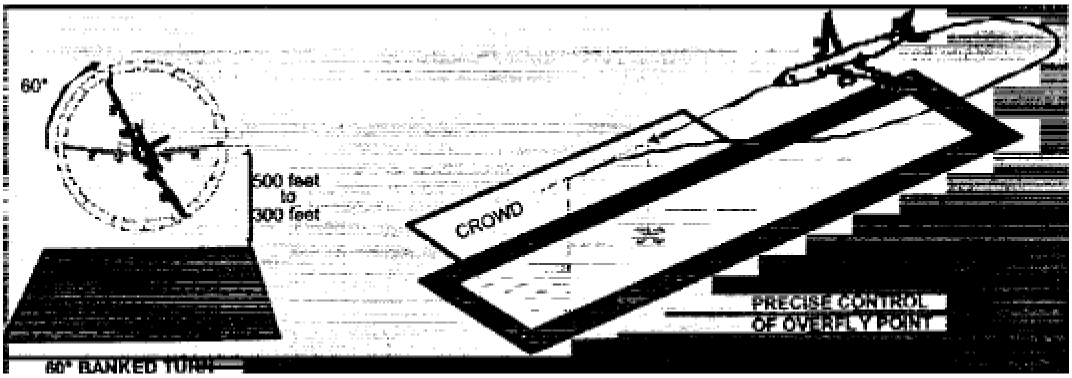


Fig. 9: Airbus systematic manoeuvres to unmask APCs [77]

As non-systematic manoeuvres, ref. [77] gives example of (see Figure 10):

Fligth dispalys



Formation flight

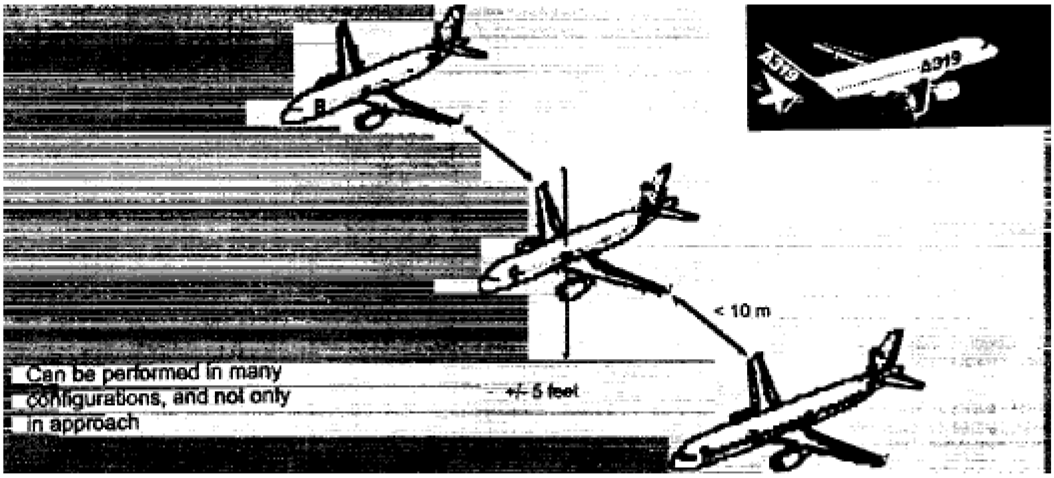


Fig. 10: Airbus non-systematic manoeuvres to unmask APCs [77]

Flight testing for RPC at helicopters has not been often catalogued in the open literature. One relevant reference in Europe on flight testing for PIOs was published by Ockier [78]. He describes three instances of moderate pilot induced oscillations that were measured during flight testing with the DLR's ATTHeS fly-by-wire helicopter . This helicopter had a minimum flying altitude of 100 ft in forward flight and 50 ft in hover. A safety pilot was there to intervene when the dangerous situations (like divergent RPCs) would develop.

The first case, discussed an attitude command configuration during a slalom tracking task (see Figure 11). This task is a relatively high gain task with necessary control inputs up to frequencies of about 4 to 5 rad/sec .The command model implemented on the ATTHeS model following control system was a critically damped attitude command model in the pitch and roll axes. In this implementation, the pitch and roll axes were fully decoupled . The basic equivalent time delay for this model was 110 msec.

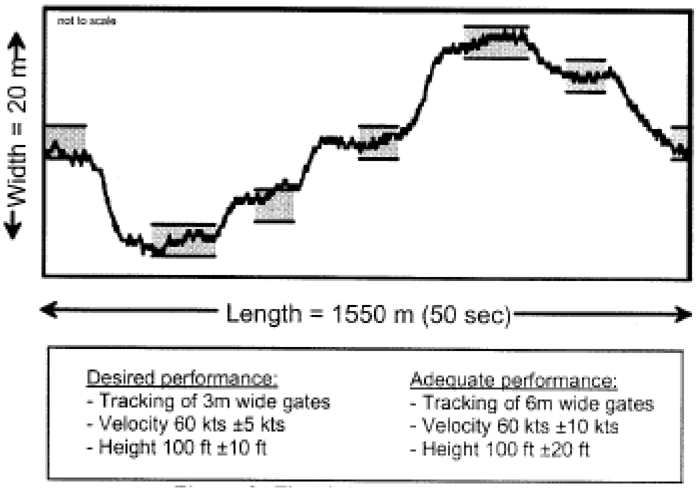


Fig. 11: Slalom tracking task performed with the DLRs ATTHeS helicopter to unmask RPC [78]

The results of this test showed that, during the gate acquisition and gate tracking phases, the pilot was using a lot of almost periodic inputs to try and maintain track within the gates . The result was an oscillatory response which was also clearly visible in the bank angle response. Although the response was not a full blown PIO, Ockier comments that "*it is a pilot sustained oscillation which demonstrates the potential for PIOs in this situation . After his evaluation flight, the pilot commented the tendency for a "roll PIO" and said this was a "very poor* *configuration" . The handling qualities rating for this case was 6, which is probably generous regarding the difficulty of controlling the helicopter through the gates.*"

The second example demonstrating the potential for PIOs was an attitude command during lateral position tracking. The task was a lateral position tracking task: A hover board mounted on a vehicle was used to guide the helicopter into a hover over a given point at a given altitude (see Figure 12) . The lateral hover tolerance was ±3 m, the horizontal tolerance was ±1 .5 m . The task was to maintain the hover position relative to the hover board while the vehicle (with the board) translated over a distance of 100 m within 20 seconds, using the velocity pattern shown below in the figure. At the end of the maneuver, a stabilized hover was to be regained. The command model implemented on ATTHeS was again the attitude command model with a basic roll axis time delay of 90 msec+100msec added time delay. For the yaw axis, a heading hold function was implemented . The control system of ATTHeS consisted of a spring loaded force feel system with very little damping, linear stick forces and relatively low breakout forces.

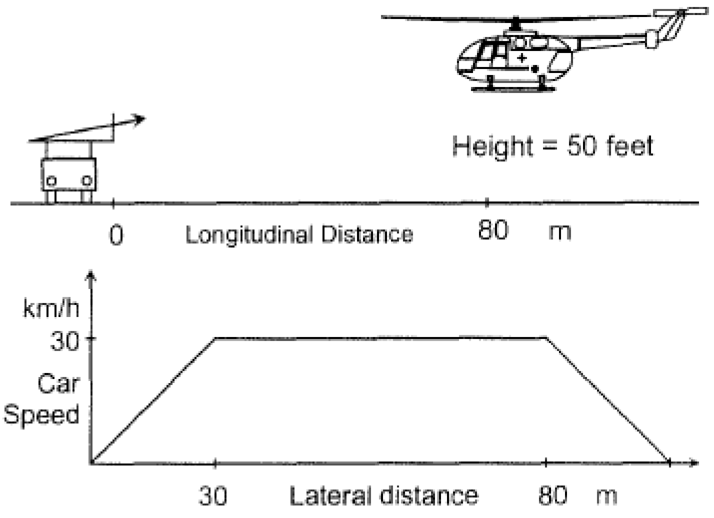


Fig. 12: Lateral positioning task performed with the DLRs ATTHeS helicopter to unmask RPC [78]

The results showed that a very clear PI0 tendency could be recognized — even when this PI0 is not divergent. Although the added time delay of 100 msec was a partial reason for the PI0, there is a more important contributor : the (bio-)mechanical coupling between aircraft and stick/pilot. This was explained by the author by examining the following sequence of events . "*When the vehicle starts its lateral translation, the pilot needs to bank to the right in order to follow the vehicle, so he makes a lateral stick input to the right and tries to maintain that stick position . The helicopter model following control system responds to the input by generating a roll rate to the right. The inertia acting on the stick and the pilot's arm now makes the stick lag this right rolling motion . Since stick position is measured relative to the helicopter, a left stick input is sensed, so the model following control system responds with a left roll rate . Now, the pilot gets into the loop and a classic PIO develops . This PIO continues until the pilot releases the stick . After that, he seems to make more open loop inputs and avoids the PIO . The pilot's reaction to this configuration was `O-Weial This configuration is not flyable' . His handling qualities rating was 7."*

The third case exemplified by Ockier was taken from a series of flight tests performed with the students of the Empire Test Pilot's School (UK). The configurations flown were so called "open loop configurations with time delay in forward flight". In these configurations, a feedforward model was implemented to modify the original control inputs . The feedforward allowed for the reduction of damping and sensitivity and for the adding of time delays. It also significantly reduced pitch-roll interaxis coupling . The feedforward was implemented without a feedback loop, so that the pilot was really flying a `basic' rate command BO 105 helicopter with unstable phugoid and other modes . The basic effective time delay of the system was 80 msec (which is mostly the effective time delay of the BO 105 with the time delay of the BO 105 actuating system).

The task used for this case was a combined slalom and tracking task, see Figure 13. The first two gates of the slalom were aimed at the evaluation of the control system in more aggressive and less precise maneuvering . The third and fourth gate required smaller inputs but more precise tracking to maintain the position through the gates.

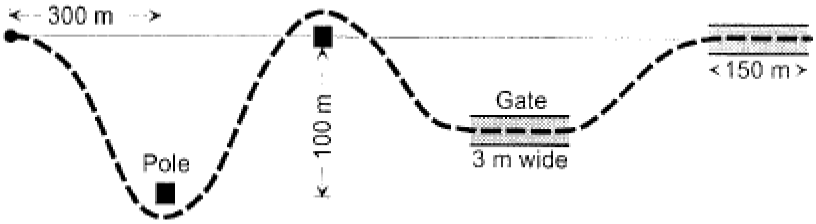


Fig. 13: Open loop configuration task performed with the DLRs ATTHeS helicopter to unmask RPC [78]

The results showed the potential for PIOs with conventionally controlled helicopters that have a time delay added to the control path.

A last point to be discussed in this chapter relates to the relation A/RPCs and Handling qualities. A/RPCs are seen by many experts as a special subset of handling qualities HQs. In fact, A/RPCs are a result of deficiencies in basic handling qualities characteristics. Because the HQs specifications define what is desirable, meeting those handling qualities specifications provides a first level of protection against A/RPCs. Ensuring good HQs of a future aircraft is closely related to A/RPC problem.

6. Conclusions

The essential elements that interact unfavourably to create a severe A/RPC event are the pilot- the aircraft-and a triggering event. Without a trigger event (or a chain of triggering events) A/RPCs do not exist. Therefore, understanding the triggers for A/RPCs phenomena is important. The present report gave an overview on the different classes of triggers that can initiate an A/RPC (environmental, vehicle and pilot triggers).

The report showed that A/RPCs can be often associated with the introduction of new designs, technologies, functions and complexities. These may introduce new triggers. New technologies such as fly-by-wire (FBW) are constantly incorporated in the aircraft. Many of these early FBW systems did have high equivalent time delays (usually as the result of input filtering) and were prone to PIOs . As a result, opportunities for A/RPCs are likely to persist or even increase, and greater attention is necessary to ensure that new technologies do not inadvertently introduce dangerous triggers, increasing the susceptibility of new aircraft/rotorcraft to A/RPC events.

The report investigated the role of simulators and flight testing in unmasking A/RPCs. Generally, use high-gain maneuvers to evaluate A/RPC tendency in piloted simulations. Also, the designer should understand the relation A/RPCs and Handling qualities (HQs). Because the HQs specifications define what is desirable, meeting the handling qualities specifications provides a first level of protection against A/RPCs. Ensuring good HQs of a future aircraft is closely related to A/RPC problem.

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8. List of Abbreviations

APC – Aircraft Pilot Coupling
ARISTOTEL – Aircraft and Rotorcraft Pilot Couplings – Tools and Techniques for Alleviation and Detection
ASE – Advanced Supersonic Transport
DVE – Degraded Visual Environment
FBW – Fly by Wire
FOV – Field of View
FCS – Flight Control System
FDR – Flight Data Recorder
HQR – Handling Qualities Requirements
OCM – Optimal Control Model
PAO – Pilot Assisted Oscillations
PF – Pilot Flying
PIO – Pilot Induced Oscillations
RPC – Rotorcraft Pilot Coupling
UCE – Usable Cue Environment
VCR – Visual Cue Rating