ARISTOTEL

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 goal of the present report is to define a database of A/RPC events containing historic and recent incidents and, based on this, to give a unified definition characterizing A/RPC events. The following definition has been given: *An aircraft- or rotorcraft-pilot coupling (A/RPC) is an unintentional (inadvertent) sustained or uncontrollable vehicle oscillations characterized by a mismatch between the pilot's mental model of the vehicle dynamics and the actual vehicle dynamics. The result is that the pilot's control input is out-of-phase with the response of the vehicle, possibly causing a diverging motion.* The report has reviewed specific fixed wing and rotorcraft-pilot coupling cases and showed the differences between these two vehicles as regards the A/RPCs.

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1. Introduction

Today's high performance aircraft are a product of ever increasing operator requirements. They are more capable, faster and more complex than their predecessors. As their complexity increases, both engineers and pilots of fixed and rotary wing aircraft must deal with an associated increased incidence of unfavourable aircraft-and-rotorcraft pilot couplings (A/RPC). Until 1995, usually known under the name of Pilot Induced/Pilot Assisted oscillations (PIO/PAO), A/RPCs are generally oscillations or divergent responses of vehicle originating from adverse pilot-vehicle couplings. These undesirable couplings may result in potential instabilities or annoying limit cycle oscillations, degrading the aircraft handling qualities and risking exceedence of its structural strength envelope. The exceedence of structural strength limits can clearly result in catastrophic failures.

Adverse Aircraft/Rotorcraft-Pilot-Couplings (A/RPC) problems have manifested themselves since the earliest days of manned flight. the earliest recorded examples of PIO's date back to the Wright Brothers first aircraft [ref 1, 31]. According to McKay [ref. 4], The earliest video record dates from just before World War II, with the XB-19 aircraft which suffered a pitch PIO on touchdown. Despite decades of work to develop methods for their prevention, unfavourable aircraft pilot couplings and rotorcraft pilot couplings (A/RPCs) continue to occur. The goal of the present report is to define and give a historical perspective of the A/RPC problems.

The goal of the present report is to review the current status of A/RPC analysis (see description task 1.1 of ARISTOTEL project) and:

- Develop a full understanding of what is meant by the term aircraft/rotorcraft pilot couplings (A/RPCs) from the designer's perspective and how such phenomena affect the safety of the aircraft/rotorcraft;
- Define a database of A/RPC events containing historic and recent incidents that demonstrate a need for safety improvements.

For example, the current dilemma whether or not a particular event is a PIO according to different existing definitions will be clarified. In this report a unified definition characterizing A/RPC events will be given, a definition which will be then used consistently to analyse A/RPCs events throughout the ARISTOTEL project.

A stepping-stone for the understanding of every A/RPC event is provided in Figure 1 which gives a block diagram representation of an elementary closed loop rotorcraft-pilot system. This classification is also illustrative for the fixed wing aircraft.

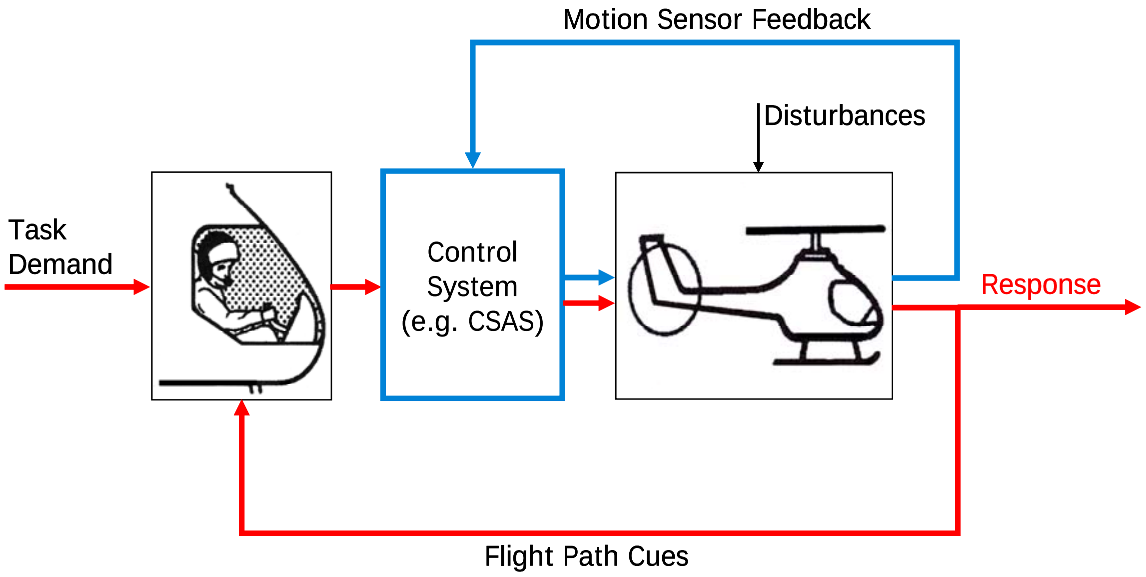

Figure 1: Pilot in the loop system for A/RPC analysis (picture from ref. [73])

A short explanation of this figure is given: The input into the system is the "Task". This can be anything from a tracking task, maneuver or forcing on the stick. The pilot uses the task to give inputs to the stick, which can be connected to the vehicle directly or through a control system (digital filters of a Flight Control System and actuators). The actuators control the vehicle control surfaces (blade pitching system in the case of rotorcraft). The controls are input for the vehicle dynamics, where the inherent dynamics of the vehicle is located. The output of the system is fed back to the pilot and the control system. The pilot or the FCS gives adjusting control inputs based on the needed states to fulfill the task.

2. Defining Aircraft / Rotorcraft-Pilot-Couplings

The most classical definition known for PIO/PAO or later for A/RPCs events was given by McRuer in the 1990's: *"A pilot-induced oscillation (PIO) is an inadvertent, sustained aircraft oscillation which is the consequence of an abnormal joint enterprise between the aircraft and the pilot"* [ref 4]. The same definition is contained also in the military standard MIL-STD-1797A "The Department of Defense Interface Standard for Flying Qualities of Piloted Airplanes" [ref. 12]: PIO consists of "*sustained or uncontrollable oscillations resulting from efforts of the pilot to control the aircraft*." It has been suggested that the word "unintentional" be added before "sustained," to distinguish from intentional oscillatory behavior.

In other words, PIOs, according to McRuer definition, are undesirable and hazardous phenomena that are associated with pilot-aircraft interactions. This definition was given during the broadest investigation on PIO problems "*Effects of Aircraft-Pilot Coupling on Flight Safety*" performed in the United States by the US NRC/ASEB Study Committee under the leadership of D.T. Mc.Ruer [ref. 3]. Although this definition has been extensively used since its introduction, it has been often highlighted in the past that, one of the major problems in A/RPCs is related to the recognition and reporting of A/RPC incidents. *"There is a tendency for pilots not to recognise the event which has occurred as a PIO or to admit or discuss the*

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[3] NRC/ASEB = The National Research Council/Aeronautics and Space Engineering Board

event, having struggled with the problem and survived." [ref. 4]. During two workshops hold in mid-1990s related to PIO problems, i.e. AGARD Flight Vehicle Integration Panel, Work Group 17 *"Flying Qualities of Unstable Highly Augmented Aircraft"* (1991) [ref 4] and Flight Vehicle Panel Workshop on "*Pilot Induced Oscillations*" (1995) [ref 5], it was concluded that the occurrence of PIO must be regarded as a failure of design process. The term PIO places an unwarranted emphasis on the pilot, when the problem is actually due to the flight control system design. Therefore, in the mid 1990s it was suggested to change and name the phenomenon as Aircraft/ Rotorcraft pilot Couplings and thus avoid the stigma which might be attached to the pilot by the unknowing and uninitiated. Thus, since 1995 it is generally accepted that A/RPCs are a result of the design process failing.

Some experts consider A/RPC problem as a subset of the field of handling qualities [ref. 6, 8]. Michel and Klyde [ref. 6] commented on that "*The design process of the airplane has matured, flight control systems have evolved, criteria and analysis techniques are available, yet PIO persists.*" [ref. 6]. The reason for this is that perhaps PIO persists because the signature of PIO is often unrecognized. Indicators of PIO may not be identified in the design process, because available measures are not used or used as intended. "*Indicators of PIO in fixed-base simulators may not be recognized because of the absence of needed cues such as the "seat of the pants" feel or anomalies are disregarded as a "feature" of the model. In flight test, higher gain or urgency maneuvers that can expose PIO indicators are often not performed, because they lack operational relevance, or so the argument goes. The end result is that PIO persists and the signature of PIO remains unrecognized."* [ref. 6]

There is a huge lack of consensus regarding the definition of exactly what is a PIO. According to McRuer [ref. 2], Pilot Induced Oscillations occur when the pilot inadvertently causes divergent oscillations by applying control inputs that are essentially in the wrong direction or have a significant phase lag with respect to the aircraft response. Such oscillations can occur in configurations that are oversensitive to pilot inputs, or have excessively low natural frequencies and low response bandwidth. As a result 'angular acceleration responses are immediate and directly coupled to the stick inputs' [ref. 7]. Since active involvement in the control loop is occurring, the pilot can stop the PIO by releasing the controls or changing his control strategy (for example reducing the closed loop gain). Pilot Assisted Oscillations (PAOs) are the result of involuntary control inputs of the pilot in the loop that may destabilize the aircraft due to inadvertent couplings between the pilot and the aircraft. PAOs are actually high order PIOs, mostly associated with 'control system effects, including additional phase lags due to inappropriate filters and (to a limited extent) digital effect time delays, excessive command path gains, and actuation system saturation. The angular acceleration responses are lagged or delayed…" [ref. 7]. PAOs that involve passive involvement by the pilot's biodynamic response to vibration can be particularly dangerous because the action of releasing the controls may be dangerous in itself. Their essence is an oscillation at a frequency where the attitude response lags the stick inputs by approximately 180 degrees. Generally, both, PIOs and PAOs are limit cycle type oscillations.

It has been argued by some experts that the introduction in the mid-1990's of the term A/RPC as a general term for pilot/vehicle destabilization, considering PIOs and PAOs as subclasses of A/RPCs, is even more confusing. "*The introduction of the term "Aircraft-Pilot Coupling" (APC, or sometimes A-PC) in the mid-1990's contributed to the obscuration of the*

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[4] AGARD =Advisory Group of Aerospace Research and Development

obvious: while the intent of this new term was to capture both oscillatory and non-oscillatory adverse behaviors of the aircraft-pilot system,1 it has further factionalized the debate as there are now questions like, "Was this event a PIO or just APC?" and "What's the difference between PIO and APC?" to be addressed in the ongoing debates." [ref. 6].

Recalling the definition given to PIOs by MIL-STD-1797A, Mitchell and Klyde [ref. 6] comment that, actually, the classic definition on PIO includes only one percept of a PIO, i.e. oscillatory behaviour of the closed-loop pilot-vehicle system. Taken literally, MIL definition states that, essentially, any oscillation that occurs during manual, piloted control may be classified as a PIO. Yet many times this oscillation is nothing more than a result of pilot overcontrol in an otherwise normal circumstance. *"For example, to the outsider the typical ballooning in flight path of a fixed wing airplane that any student pilot encounters during landing training may appear to be a PIO. This ballooning is simply part of standard pilot compensation and is usually no more than one or two cycles, with no threat of developing into a life threatening PIO. Indeed, visual inspection of the time history records from even the experienced pilot in the landing flare with a known good airplane will reveal small corrections that might appear to be signs of a PIO. These are not what MIL-STD-1797A is referring to, nor are they to be feared."* The authors argue that, because of the critical importance of distinguishing between a potentially catastrophic PIO and nuisance oscillations, one solution is to change the initial MIL-STD-1797A definition of PIO. The primary emphasis should be to make a distinction between closed-loop pilot/aircraft oscillations that are a side effect of the pilot's tracking effort and those that have a potential for loss of control. In other words, one has to distinct between the case in which the pilot drives the oscillation and the case in which the pilot is driven by the oscillation as in a "real" PIO. These oscillations may look identical on recorded data, but according [ref. 6] only the pilot can properly make this crucial distinction. Ref. 6 suggests further to consider that a new task has been created (stop the oscillation) if the oscillation requires that the pilot redirect efforts away from the primary task by a noticeable amount. In such cases the pilot is being driven by the oscillation (forced to do a new task) and is in a real PIO.

To the initial oscillatory characteristics percept for PIO introduced by the classical PIO definition, Mitchell and Klyde [ref. 6] add a new important principle, i.e.out-of-phase behaviour. The example given for considering out-of-phase behaviour as percept for A/RPC event is simple and relevant. Many of the PIOs recorded in older (1950s and earlier vintage) aircraft are traceable directly to low inherent damping of the short period or Dutch roll. Many of these PIO-like oscillations analysed by the authors could be considered in fact residual oscillations *(hands off controls)*, i.e. oscillations that continued even if the pilot was no longer making an effort to control the aircraft (as the military standard is stating) and they are not PIO. However, the distinction between true PIO oscillations and residual oscillations can become fuzzy if the cause of the residual oscillations can lead to a PIO[5]. Therefore, the authors deliberate further that "*Since the PIO is evidence of an undamped closed-loop, pilot-vehicle oscillation, then there must exist during the PIO at least one measurable aircraft state that is 180 degrees out of phase with at least one pilot control. This leads to the following proposed definition: A PIO exists when the airplane attitude, angular rate, normal*

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[5] *In most instances these oscillations were the result of low modal damping (short period or Dutch roll), and, while explicit evidence of PIO could not always be located, it is recognized that low damping of these modes may lead to PIO in closed-loop piloted control. [ref. 6]*

acceleration, or other quantity derived from these states, is approximately 180 degrees out of phase with the pilot's control inputs."

Concluding, two percepts need to be introduced in order to define A/RPC: 1) oscillatory behaviour and 2) out-of-phase behaviour of at least one aircraft state with at least one pilot control.

3. Database of A/RPC events

This chapter gives an overview of A/RPC events gathered from the open literature and from accident investigations. Table 1 presents a database of aircraft (fixed wing. Shuttles, gliders) APCs events collected from open literature and accidents investigation reports. Table 2 presents a database of rotorcraft (helicopters, tiltrotors and gyrocopters) RPCs events collected from open literature and accidents investigation reports.

As can be seen from Table 2, most RPC events involve larger rotorcraft with conventional (nondigital) flight controls. Furthermore, they are associated with couplings of the pilot with lower flexible modes or an external underslung load. It is probable that newer types of rotorcraft with digital flight by wire (DFBW) like the NH90 will also appear in the table, these types of rotorcraft are equipped with a full or limited authority flight control system (FCS), possibly with rate limiting elements (RLEs). Furthermore, longer time delays in the control loop due to digital filtering will also be present. This makes the modern helicopters more prone to Category I, II and III RPC events [23, 35, 37].

Table 1 Database of APC events

Type of Aircraft *	Accident Year	Exact Accident Date	Aircraft Model	Experienced PIO/PAO	APC Type	Accident Report/Database Reference **
F	1947	October 24, 1947	XS-1	PIO during gliding approach and landing	PIO	[ref.40]
F	1949	Early 1949	XF-89A	PIO during level off dive recovery	PIO	[ref.39]
F	-	-	F-86D	PIO during formation flying- pulling G's	PIO	[ref.39]
F	-	-	F-100	PIO during tight maneuvering	PIO	[ref.39]
F	-	-	F-101	Aft CG		[ref.39]
F	1952	March 31, 1952	X-15	-		[ref.41, 42]
F	-	-	A4D-1 Skyhawk	Low Altitude; near sonic Mach -Cat I:Arm mass increases feel system inertia; leads via bobweight feedback to unstable coupling with short period dynamics if pilot merely hangs loosely onto the stick after large input	PIO	[ref.58]

F	-	-	C-97 Strato-freighter	Approach; Landing - Cat I:Lag from radar-detected error to voice command led to unstable closed-loop phugoid mode. Critical subsystems included display and vehicle airframe dynamics	PIO	[ref.58]
F	-	-	Curtiss SB2C-1	Cruise -Cat II: Porpoising (unable to maintain flight path), Hysteresis in stick versus elevator deflection resulted in low frequency speed and climb oscillations	PIO	[ref.58]
F	1957	January 19, 1957	A4D-2	High speed category III PIO, during routine flight testing	PIO	[ref. 55, 56]
F	1958	1958	KC-135A	Mild Lateral-directional PIO associated with w_{Φ}/w_d effects	PIO	[ref.49]
F	-	-	B52	Roll PIO while refueling	PIO	[ref.39]
F	1958	1958	F-101B	Lateral PIO at high q subsonic	PIO	[ref.50]
F	1959	June 8,1959	X-15	Gliding flight approach, Category II PIO	PIO	[ref.42, 43]
F	-	-	XY2FY-1	Post-take off destructive PIO	PIO	[ref.39]
F	1960	January 26, 1960	T-38	High speed category III PIO, distributed Bobweight and Primary control system involved	PIO	[ref. 58, 43, 59, 60, 61, 62]
F	-	-	X-15; T-33VSA; F-101B; F-106A; KC-135A; B-58;	Cruise -Cat I: Zeros of roll/aileron transfer function are higher than Dutch Roll frequency, leading to closed-loop instability at conditions with low dutch roll damping. Due to airframe dynamics	PIO	[ref.58]

F	-	-	XF-10; F-101B; F-102A	Cruise - Cat II: Pitch up due to unstable kink in the alpha-moment curve. Led to moderate period oscillations of varying amplitudes during manouevres at the critical angle of attack	PIO	[ref.58]
F	1960	-	B-58	Lateral Ducth Roll oscilaltions lead to lateral PIO due to actuator limiting of AFCS	PIO	[ref.74]
F	1961	1961	X-15	Lateral PIO , w_{Φ}/w_d Research study	PIO	[ref.39]
F	1961	May 18, 1961	F-4	Low altitude record run seconds pass, destructive PIO	PIO	[ref.39]
G	1962	1962	Parasev	Lateral rocking PIO during ground tow	PIO	[ref.40]
F	1962	September 14, 1962	B-58	Lateral-directional control-associated crash	PIO	[ref.39]
F	-	-	T-38A Talon	Low Altitude; near sonic Mach -Cat I: Arm mass increases feel system inertia; leads via bobweight feedback to unstable coupling with short period dynamics if pilot merely hangs loosely onto the stick after large input	PIO	[ref.39]
F	1967	may 10, 1967	M2-F2	Lifting body lateral-directional category II PIO	PIO	[ref.52, 53]
S	1967	October 1967	Shuttle	ALT-5 lateral PIO, just prior to longitudinal PIO	PIO	[ref.43, 46]
F	1968	-	Transport A/C	PIO due to the insufficient stability margin+ aero-elasticity	PIO/ PAO	Russia
F	-	-	Transport A/C	PIO during landing	PIO	Russia
F	-	-	Transport A/C	High-frequency PIO (3 Hz). Interaction between pilot+ wheel characteristics+ aero-elasticity	PIO/ PAO	Russia

F	-	-	F-18	MTE (A-2-A Refueling) -PIO on A-2-A refueling exercises on early version of FCS	PIO	[ref.2]
F	-	-	Fighter A/C	PIO during pitch stabilization. Interaction between pilot+ manipulator+ feel system characteristics	PIO/ PAO	Russia
F	1974	-	YF-16	On-ground (Taxi) - Unplanned first flight during high-speed taxi test	PIO	[ref.2]
F	-	-	YF-12	Category III PIO	PIO	[ref.43, 44]
F	1975	-	MRCA	Short Take off -Heavy Landing		[ref.39]
F	-	-	YF-12	High frequency flexible mode involvement, Category I PIO	PIO	[ref.43, 44]
F	-	-	A-6	Lateral effective bobweight effects		[ref.39]
F	-	-	Fighter A/C	PIO during roll stabilization task (0.4 Hz). Interaction between yaw and roll	PIO	Russia
F	1976	January 26, 1976	Tornado	Landing -Landing accident during flight test of prototype no.5		[ref.2]
S	1977	October 26, 1977	Shuttle	ALT-5 during landing approach, Category III PIO	PIO	[ref.45, 46]
F	1978	April 18, 1978	DFBW F-8	PIO during touch and goes		[ref.70]
F	-	-	Transport A/C	High-frequency roll ratchet (2.5 Hz). Interaction between pilot+ manipulator+ aero-elasticity	PIO/ PAO	Russia
F	1978	-	Fighter A/C	PIO (0.8 Hz) due to the too high control sensitivity during flight tests	PIO	Russia
F	-	-	YF-16	First flight, Category III PIO	PIO	[ref.53, 43]

F	-	-	DFBW F-8	Landing [Touch and Go Operation] - Category III PIO during a touch and go landing and take-off exercise	PIO	[ref.2]
F	-	-	Airbus A-320	Several undocumented PIOs that reportedly occurred during development	PIO	[ref.2]
F	-	-	Northrop F-5A Freedom Fighter	Cruise -Cat I: Spiral mode driven unstable if roll information is degraded during gunnary. Driven by Display and vehicle	PIO	[ref.58]
F	1986	-	Voyager	Pilot Coupling with symmetric Wing Bending	PIO	[ref.63]
F	1986	-	Fighter A/C	PIO (0.8 Hz) due to the too high control sensitivity	PIO	Russia
F	-	-	F-86D; F-100C	Low Altitude; near sonic Mach- Cat II: Valve friction plus compliant cabling resulted in large oscillations at abort period	PIO	[ref.58]
F	-	-	Douglas A3D	Low Altitude; near sonic Mach; Cruise-Cat II: Transonic snaking. Seperation over rudder causes control reversal for small deflections, leading to limit cycle if rudder used to damp yaw oscillations. Due to airframe dynamics and feel system	PIO	[ref.58]
F	1988	December, 1988	JAS-39 Gripen	Approach -Heavy turbulence with inexperienced pilot. Pilot was controlling flight path angle and met insufficient control power, inducing rate limiting. Resulted in crash and destruction of test aircraft	PIO	[ref.39]

F	1990	1990	JAS 39	PIO during approach	PIO	[ref.39]
F	-	-	F-111	Pilot lateral control coupling with sustained under wing heavy store limit cycle oscillation	PIO	[ref.63]
F	-	-	F-14	High angle of attack, with some sideslip angle		[ref.39]
F	-	-	C-17	Approach; Landing - Numerous events, some with damage to wings, flaps, engine nacelles, landing gear		[ref.6]
F	-	-	AD-1	Oblique wing		[ref.39]
F	1991	-	Tu-154M	Roll PIO during landing due to high control sensitivity between pilot and lateral side-stick characteristics	PIO	[ref.72]
F	1992	April 25, 1992	YF-22	PIO after touch down and wave off in afterburner, Category III PIO	PIO	[ref.47]
F	1992	March 22, 1992	Antonov AN-30	Long+Lat PIO	PIO	Russia (CAA)
F	1993	April 6, 1993	MD-11	Inadvertent slat deployment	PIO	[ref.48]
F	1993	-	JAS-39	MTE (Low Altitude Flight) -APC event during low altitude flight demostration		[ref.2]
F	1994	-	B-2	Approach; Landing; A-2-A Refueling		[ref.2]
F	1995	April 28, 1995	Airbus Industries A320	Lateral Oscillation	PIO	NTSB: CHI95IA138
F	1995	-	Boeing B-777	Several PIOs during development flight test; pitch oscillation at touchdown triggered by deployment of spoilers, pilot's use of a pulsing technique to control a 3 Hz bending mode, oscillations after take-off triggered by mistrimmed stabiliser	PIO	[ref.2]

F	1996	April 6, 1996	MD-11	Pilots attempt to recover from slat extension lead to violent longitudinal PIO	PIO	NTSB: A-93-143/152
F	1996	1 February, 1996	Beech Baron	PIO in the landing	PIO	[ref.6]
F	1996	June 26, 1996	F-16 DBTC	Display induced PIO during terrain following	PIO	[ref.6]
F	1996	-	C-17	Roll PIO on Landing	PIO	[ref.76]
F	1997	July 31, 1997	MD-11	Longitudinal PIO during landing	PIO	J-AIB: JAL 706-1997
F	1997	June 8, 1997	MD-11	Captain indicated longitudinal PIO	PIO	[ref.6]
F	1998	-	Boeing 757	Lateral Oscillations during approach and landing	PIO/ PAO	[ref.6]
F	1999	January 15, 1999	Boeing 767	Buckled fuselage during landing		[ref.6]
F	1999	March 8,1999	F-18F	FCS modifications made due to landing on carrier	PIO	[ref.6]
F	1999	October 9, 1999	Falcon-900	PIO during decent	PIO	[ref.6]
F	1999	January 15, 1999	Boeing 767-300	Longitudinal PIO	PIO	AAIB: EW/C991301
F	1999	September 14, 1999	DASSAULT-BREGUET - FALCON 900	Pilot convicted of manslaughter during decent		Romania(CAA): 1999091401
F	2001	February 8, 2001	A321	PIO during landing, damaged wing tip, fence and ailerons	PIO	[ref.6]
F	2001	July 1, 2001	X-35B JSF	Category I PIO during hover	PIO	[ref.6]
F	2001	-	C-17A	PIO's during approach and landing	PIO	[ref.6]
F	2001	March 17, 2001	AIRBUS INDUSTRIES - A320	PIO during take off	PIO	NTSB: CHI01FA104
F	2001	June 7, 2001	LEARJET - 24	Lateral Oscillation		NTSB: LAX01TA204
F	2002	December 7, 2002	A321	PIO during landing	PIO	[ref.6]
F	2002	-	T-45	Directional PIO on Landing Rollout	PIO	[ref.75]
F	2004	October 28,2004	F/A-22	PIO during Air-to-Air tracking	PIO	[ref.6]
F	2008	September 27, 2008	Sport Flight International Astra	Yaw oscillations during landing		NTSB : SEA08CA212

F	2008	July 31, 2008	Aero Commander 200D	Inadvertent pilot-induced oscillation during the landing flare/touchdown	PIO	NTSB : CHI08CA225.
F	2008	January 10, 2008	AIRBUS INDUSTRIES - A319	Lateral Oscillation		EASA: A08W007
F	2009	August 31, 2009	Cessna C 152	Student pilot initiated a longitudinal PIO during flare	PIO	NTSB:WPR09CA430
G	2009	June 29, 2009	SCHEMPP-HIRTH VENTUS	Released from towplane and encountered a longitudinal PIO	PIO	NTSB: WPR09LA317
G	2009	January 16, 2009	GLASER-DIRKS DG-400	Pitch oscillation during cruise		NTSB: WPR09FA089
F	2009	November 06, 2009	CIRRUS SR20	The pilot's improper flare initiated a longitudinal PIO	PIO	NTSB: WPR10CA054

** **F**: Fixed Wing, **S**: Shuttle, **G**: Glider*

*** **NTSB:** National Transportation Safety Board, **AAIB:** Air Accidents Investigation Branch*
***J-AIB:** Japan Accident Investigation Board, **EASA:** European Aviation Safety Agency*

Table 2 Database of RPC events

Type of Aircraft *	Accident Year	Exact Accident Date	Aircraft Model	Experienced PIO/PAO	RPC Type	Accident Report/Database Reference **
H	1964	-	Bo-46	Rotor control/gyro system coupling		[ref.11]
H	1967	-	CH-46D	Flexible mode air resonance "Shuffle Mode"		[ref.11]
H	1967	-	CH-46D Sea Knight	3.2Hz 'shuffle' oscillation. Out of phase coupling of rotors w/ aft pylon fuselage mode; changes made to the aircraft and operations	PAO	[ref.11]
H	1968	-	CH-47	Rotor/Sling load bounce		[ref.11]
H	1970	-	AH-56	Flexible Control Actuation system		[ref.65]

H	1978	1978-1985	CH-53E	APC with Flexible Modes, several major instances in precision hover and with heavy sling loads, including heavy landings, dropped loads. Extreme Category I to Category II PIOs	PIO	[ref.66, 71]
H	1978	-	CH-53 E (USN)	Flexible Modes/Sling Loads		[ref.66]
H	1980	-	CH-53 G (GAF)	Flexible Modes/Sling Loads	PAO	[ref.67]
H	1980	-	CH-46E	Flexible mode-air resonance "Shuffle Mode"		[ref.11]
H	1981	-	SH-60	Flexible mode ground resonance		[ref.11]
H	1988	-	UH-60 ADOCS	Excessive Time Delays		[ref.68]
T	1989	-	V-22	3.0 Hz roll mode; coupling with roll and main rotor system's regressive lag mode; LAO from large aft rotor flapping. Procedural centering of control stick, reducing rotor flapping and increased rotor lead-lag damping	PAO	[ref.64]
T	1990	-	V-22A Osprey [FSD]	3.2 Hz Asymmetric wing chord mode due to aerodynamic phenomena; coupling with lateral cyclic inputs; addition of a notch filter at 3.2 Hz	PAO	[ref.11]
T	1991	-	V-22A Osprey [FSD]	3.8 Symmetric wing chord bending mode w/ 4000 lb load; pilot coupling through longitudinal cyclic; Notch filters introduced at frequency	PAO	[ref.11]

T	1991	-	V-22A Osprey [FSD]	4.2 Hz symmetric wing chord mode coupled with the pilot Thrust Control Lever (commanding rotor collective); minor coupling at 5.3 Hz with symmetric wing torsion mode. Asymmetric notch filters added	PAO	[ref.11]
H	1992	-	S-76B	Flight control mode shifting	PIO	[ref.11]
H	1993	-	BO 105 ATTHeS	Time delay/Attitude Command		[ref.69]
H	1994	June 02, 1994	BELL 47D-1	Pilot inducted lateral oscillation due to heavy cyclic control forces in hover	PIO	NTSB : LAX94LA235
H	1995	-	BO 105 ATTHeS	Biomechanical/Airframe coupling	PAO	[ref.11]
T	1997		V-22B Osprey [EMD]	1.4 Hz High Focal Roll mode oscillation due to change in mass balance weight; relaxation of pilot gripon cyclic	PAO	[ref.11]
H	1998	December 03, 1998	Eurocopter EC-135-P1	Helicopter encountered wake turbulence of a MD 80 airplane and PIO's occurred during recovery	PIO	NTSB : NYC99FA032
T	1999	February 2, 1999	V-22	Hover over ship	PAO	[ref.6]
H	2000	August 08, 2000	Bell OH-58C	PIO during a practice autorotation	PIO	NTSB : ATL00TA080
H	2000	December 18, 2000	SA365-N1	Longitudinal and lateral PIO during landing		NTSB : NYC01LA059
G/C	2003	4/23/2003	DENZER RAF 2000	Abrupt lift-off caused longitudinal PIO during take off		NTSB : ANC02FA064
G/C	2003	January 01, 2003	Air Command Commander Elite	Inadvertent phugoid pilot induced oscillation due to wind gust	PIO	NTSB : CHI03LA048.
G/C	2003	November 16, 2003	Northam RAF 2000	Longitudinal oscillations during level flight		NTSB : NYC04LA035.
H	2003	June 28, 2003	Schweizer 269C	Lateral Oscillation		NTSB : DEN03LA115.

H	2004	May 08 ,2004	Robinson R44	Longitudinal PIO due to experiencing low cyclic force while initiating a hover after take off	PIO	AAIB: G-CBXX
H	2005	August 13, 2005	Robinson R44	The inadequate remedial action during landing by the pilot caused pitch oscillations	PIO	NTSB : CHI05LA235.
H	2006	January 10, 2006	Eurocopter AS350BA	Yaw initiated PIO caused helicopter to crash	PAO/ PIO	NTSB : LAX06LA072
H	2006	October 16, 2006	Robinson R22 BETA	PIO in yaw axis started during cruise flight		NTSB : DEN07CA013.
H	2007	December 05, 2007	Bell UH-1B	Pilot caused vertical oscillations due to collective bounce	PAO/ PIO	NTSB : SEA08LA043.
H	2008	May 01, 2008	Robinson R22 Beta II	Student pilot started a lateral PIO in hover		NTSB : LAX08CA126
H	2008	June 29, 2008	Bell UH-1B	Collective bounds lead to vertical oscillations during autorotation	PAO/ PIO	NTSB: ANC08LA083
H	2009	May 12, 2009	Robinson R44	Initiated yaw oscillations turned into yaw-pitch PIO		NTSB:ANC09GA040
H	2009	November 15, 2009	Robinson R44 Astro	Inexperienced pilot caused mixed PIO		AAIB: G-WEMS

* ***H**: Helicopter, **G/C**: GyroCopter, **T**: Tiltrotor*

** ***NTSB**: National Transportation Safety Board, **AAIB**: Air Accidents Investigation Branch*

As an illustration of some of the A/RPC characteristics, consider next some sets of traces corresponding to famous A/RPC examples. The first example is the YF-22 APC event; see Figure 2 (from ref [2]) and Table 1. This military fighter aircraft was part of USAF Advanced Tactical Fighter program during the late 1980s.

Its initial control laws and command structure were relatively conventional and very similar to the ones in the F-16, which was the first fighter aircraft to have Fly-By-Wire (FBW) and digital flight control. The control laws were designed with relatively simple tools like the Control Anticipation Parameter (CAP) and in the flight simulator environment. After the prototype was built and more enhanced parameter identified aerodynamic and propulsion models became available, thrust vectoring by nozzle control was added. This would give the aircraft better maneuverability. With this new feature, the laws and structure of the FCS were also extended and enhanced, adding in overall complexity. But still, basic design was based on flight simulator data. During flight testing in 1992 with the prototype aircraft the pilot decided to make a go-around during a low approach. He selected full afterburner and retracted the gear which automatically engaged thrust vectoring and changed the gain schedule of the command stick. The aircraft started to oscillate around the pitch axis just above the ground at 40ft. After 4 or 5 oscillations, the aircraft impacted on the ground. Figure 2 presents the time histories of the states and control inputs that were reconstructed from flight recorder data (APC starts at about 4 seconds).

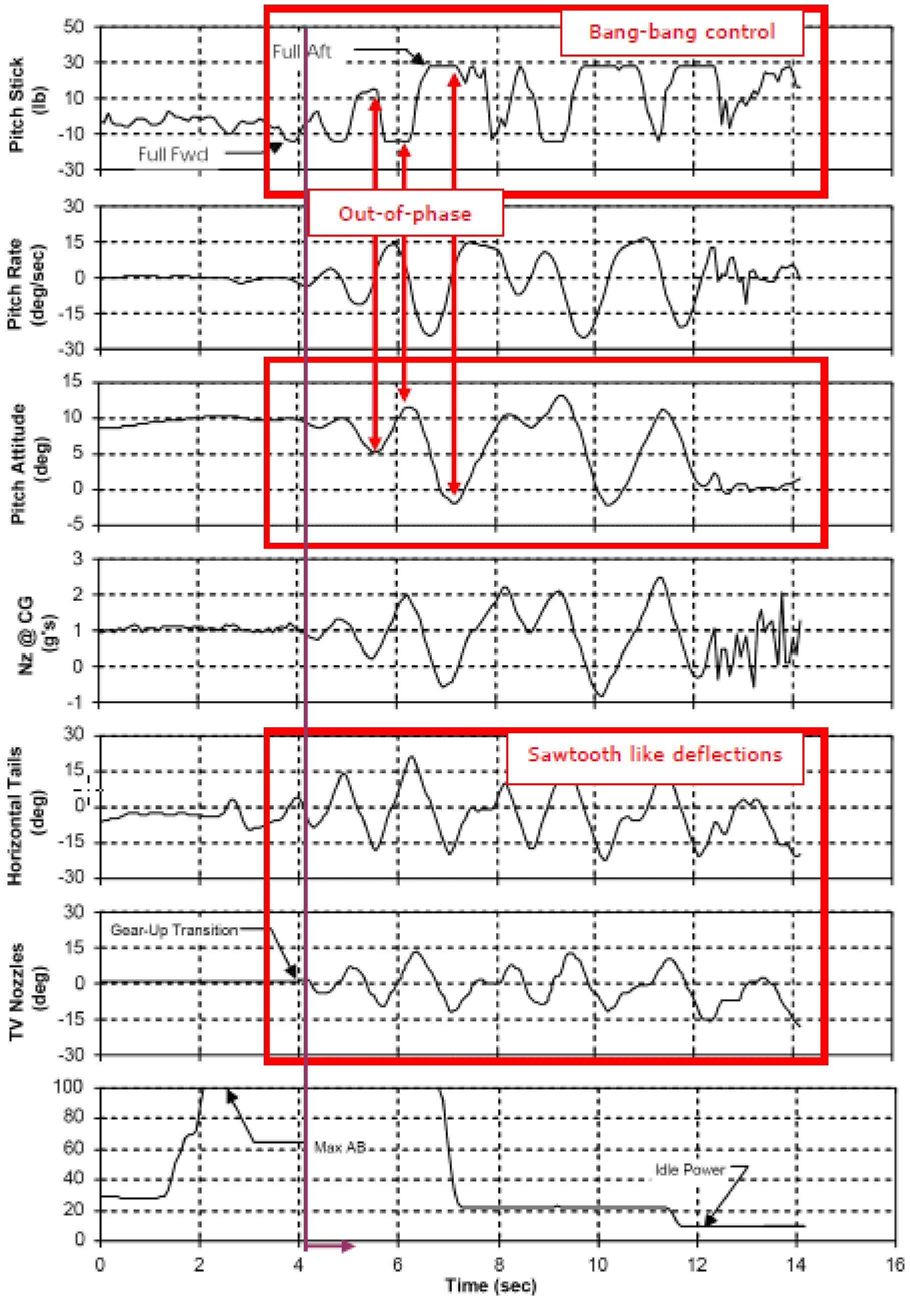
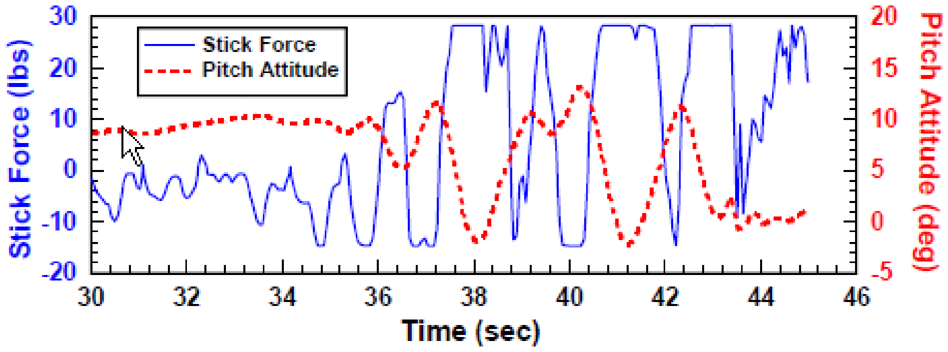


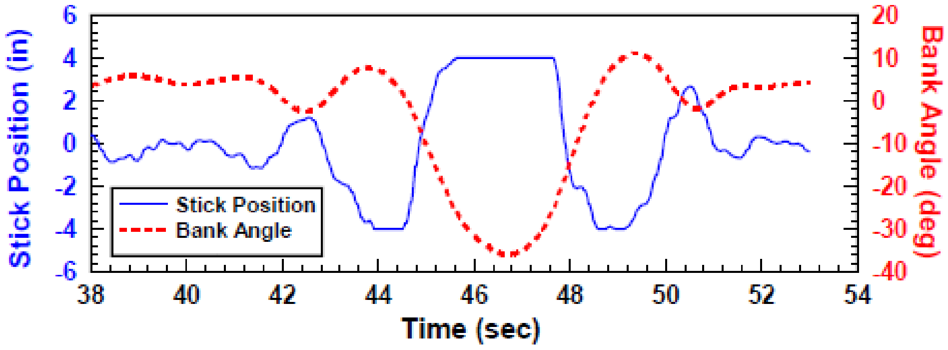
Figure 2: YF-22 APC event in 1992 (taken from [2])

As can be seen in the figure, the pitch stick inputs and the pitch attitude are out-of-phase which is a typical signature of A/RPC events. Also, after the APC was triggered, the pilot stick input exhibits bang-bang control (max-min or on-off control), increasing the closed loop gain and destabilizing the system even more. It can be said that the pilot is behaving synchronous with the response. Another signature in time histories typical for A/RPC events is the *saw tooth* like deflections (see Figure 2); this indicates control rate limiting. Just before the accident, the aircraft exhibited perfectly fine handling qualities according to the pilot. It received a Level 1 rating ("excellent") on the Cooper Harper Handling Qualities Rating (HQR) scale during other flight tests. The pilot commented that he suspected a failure and felt "disconnected from the stick" during the APC event. During post-accident analysis, the aircraft was checked against APC criteria like the Bandwidth/Phase Delay criterion. It was later shown that the YF- 22 was definitely prone to APC in that specific flight regime [27].

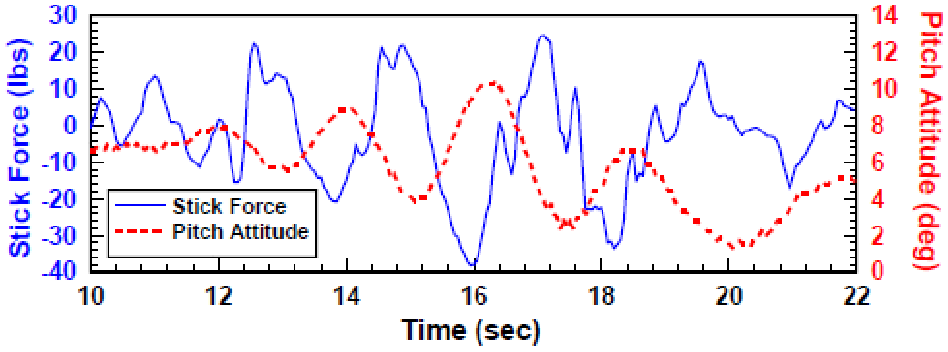
Pilots mentioning feelings like "being disconnected from the stick" or suspecting aircraft failures is not rare in A/RPC events [4]. This confirms the suspicion that the proposed mental mismatch is key for triggering and sustaining A/RPC events. As underlined by Mitchell and Klyde in ref. 6, there are actually two precepts for A/RPCs that one can read from the time traces of A/RPC accidents: 1) oscillatory characteristics; and 2) out-of-phase behaviour. Figure 3, from ref. 6 illustrates this out-of-phase behaviour characteristic to every A/RPC for the above-presented YF-22 accident (1992) and also for other two accidents, the roll PIO of an MV-22 near a ship4 in 1999; and a pitch PIO9 of an F-14A, operating on its backup flight control module, while attempting an in-flight refueling in 1990.



a. YF-22 (1992)



b. V-22 (1999)



c. F-14 BUFCM (1990)

Figure 3: Input-output pairs for three well-known PIO events showing out-of-phase oscillatory characteristics [from ref. 6]

From Figure 3 one can read the stick inputs (force or position) and the angular attitude outputs for these three cases. While there is evidence of high-frequency control activity on all of the stick traces in Figure 3, a lower frequency, sinusoidal oscillation is evident as well. Angular attitude is approximately 180 degrees out of phase with stick at the start of the oscillations, and in all cases is more than 180 degrees out of phase by the end of the traces.

The next example corresponds to a rotorcraft RPC and took place during flight testing with the Bo105 ATTHeS (Advanced Technologies Testing Helicopter System) at DLR [ref 28]. The RPC took place during a slalom task and was caused by an added time delay of 160ms in the pilot input. The time history is shown in Figure 4. To demonstrate that the time delay caused the RPC, ref. 29 plotted the time histories of the lateral position tracking task without and with a 100 ms added time delay (see Figure 5). During the task, the pilot had to track the relative position with respect to a moving vehicle, while flying sideways. It was demonstrated that this RPC (1.2Hz) was caused by combination of excess time delay and a biodynamic coupling between the pilot's arm and the lateral accelerations of the rotorcraft.

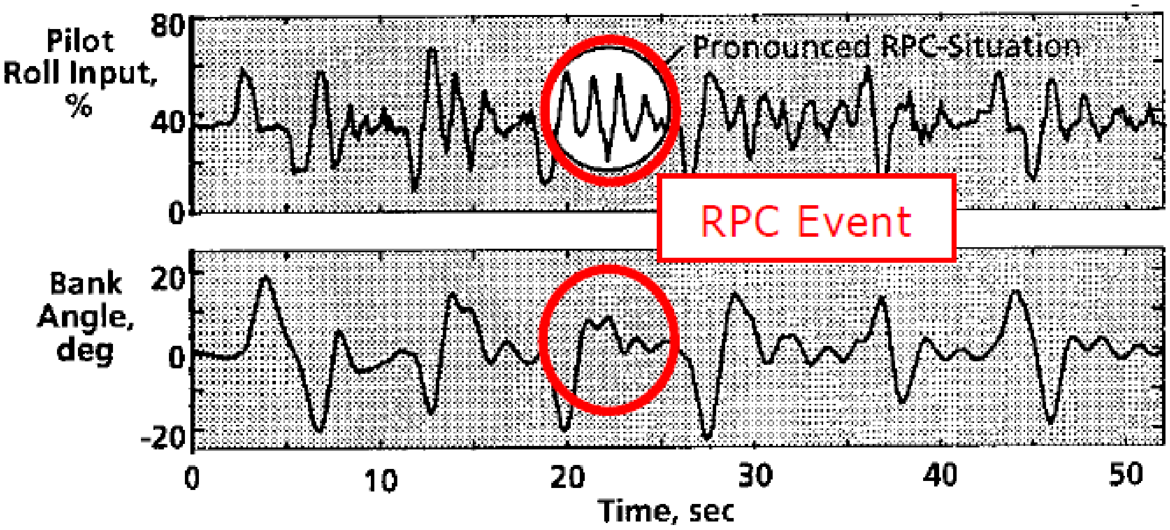


Figure 4: Bo105 ATTHeS roll attitude tracking tasks with 160ms added time delay (taken from [28])

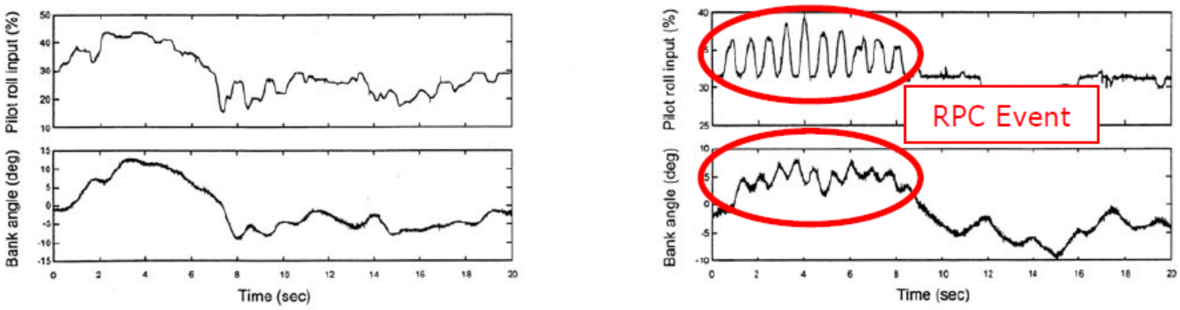


*Figure 5: **Left**: Bo105 ATTHeS lateral position tracking tasks; **Right**: Bo105 ATTHeS same lateral position tracking tasks with 100ms added time delay [29]*

The last example from the literature corresponds to a precision slope landing (very high gain task) with the UH60 ADOCS (Advanced Digital Optical Control System). In this case the helicopter encountered a RPC due to large time delays (Category I). The time history of the control input is plotted in Figure 6 from [ref. 11].

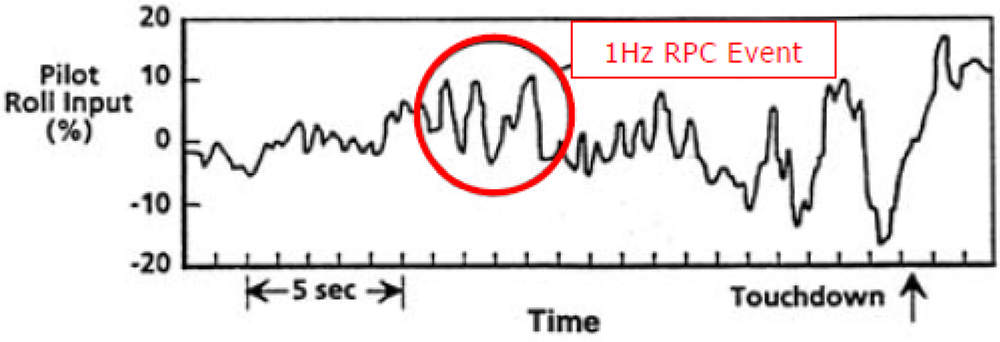


Figure 6: Vertical landing task [from ref. 11]

As suggested in ref. 6, "*Because of the critical importance of distinguishing between a potentially catastrophic PIO and nuisance oscillations, one solution is to change the definition of PIO. The primary emphasis is to make a distinction between closed-loop pilot/aircraft oscillations that are a side effect of the pilot's tracking effort and those that have a potential for loss of control. These oscillations may look identical on recorded data, and only the pilot can properly make this crucial distinction…. One way of viewing the crucial distinction between oscillations resulting from degraded handling and those that can result in a divergent PIO is to note that in the former case the pilot drives the oscillation, whereas in a "real" PIO (as defined here) the pilot is driven by the oscillation. If the oscillation requires that the pilot redirect efforts away from the primary task by a noticeable amount, we say that a new task has been created (stop the oscillation). In such cases the pilot is being driven by the oscillation (forced to do a new task). In extreme cases (e.g., YF-22 and JAS 391), the pilots thought that they had experienced a flight control system failure, and that the new task was to cope with that failure. This is the phenomenon that we must quantify if we are to achieve clarity on the difference between degraded handling qualities and PIO.*"

4. Three key elements

There are three key interacting elements or conditions that have to exist for an A/RPC to develop [2, 4, 5, 30], see Figure 7.

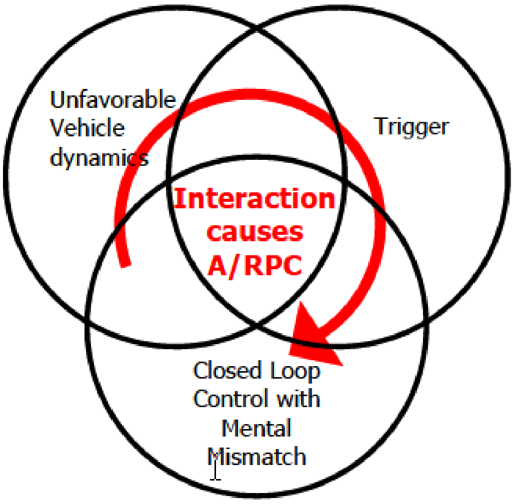


Figure 7: Three necessary conditions for A/RPC

The first necessary element for an A/RPC event to occur, is unfavorable vehicle dynamics. This means that the vehicle system as a whole, including the FCS, displays, actuators, etc., should be prone to time delay or phase lag build-up. Design criteria focus on identifying and restricting or eliminating this condition. However, every aircraft or rotorcraft can be made prone to A/RPC as long as excessive time delays or phase lags are incorporated into the vehicle dynamics. This however also reduces controllability. Time delays are for example caused by digital control filters. For example, the mentioned YF-22 had a high control gain, which made it sensitive to control inputs.

The second necessary element for an A/RPC situation to occur, is a triggering event. Usually, these are unexpected responses that disturb the vehicle state or control, like the onset of a rate limiting element [32, 33] or a shift in command type by the flight control system. These events cause the mentioned mental mismatch to arise and are the catalyst for closed loop control. Other examples of triggers are atmospheric disturbances, pilot's shift attention during aerial refueling tasks when moving attention from the horizon to the boom or basket, shock reactions near boundaries, etc. An example for rotorcraft is the shift in command type in a Weight-on-wheels situation [22, 23]. The trigger in the YF-22 case was the sudden change in control gain schedule and the engaging of the thrust vectoring system.

Third and last key element is that the pilot exercises closed loop control in an attempt to stabilize the vehicle after the occurrence of the trigger. During these attempts the pilot actually tries to control a vehicle with different dynamics (the one in his mind), so the oscillation of the actual vehicle can quickly grow in amplitude. If the pilot backs out from the control loop, the A/RPC will cease. One can well imagine that the pilot of the YF-22 thought there was an aircraft failure. This is a valid reason not to back out from the loop and to try to regain control, especially at 40ft above the ground. This mental mismatch caused the oscillation to diverge and finally the aircraft to crash.

Based on the many comments from the industry, [ref. 6] suggested the following ten features (definitions) characterizing virtually every APC documented in the open literature:

1. PIO is a sustained or uncontrollable unintentional oscillation resulting from the efforts of the pilot to control the aircraft. This is the MIL-STD-1797A definition, with the word “unintentional” added.
2. PIO occurs when a response state of the airplane is approximately 180 degrees out of phase with the pilot. It could be any response state of the airplane, the most common for fixed wing aircraft are pitch attitude, roll attitude, and load factor [ref. 6]
3. PIO is an event that results from faulty aircraft design, extension of the airplane’s operational usage into an area for which it was not intended, or following a failure, and is not the fault of the pilot.
4. PIO is commonly found to be related to deficiencies in basic flying qualities characteristics, though it should be treated independently from flying qualities. Most PIOs outside of the research world are related to rate limiting of a control effector or software element upstream of a control effector, but rate limiting can be both the cause of PIO and the result of it.
5. PIO may be either constant-amplitude, convergent, or divergent with time.
6. PIO may be any number of cycles of oscillation; there is no minimum number to declare it a PIO.

7. PIO may occur at very low frequencies – near the phugoid mode in pitch – up to frequencies of around 3 Hz (“roll ratchet”). The most common frequency is in the range for pilot closed-loop control, typically 1/6 Hz to slightly above 1 Hz (1 rad/sec to 8 rad/sec), but frequency alone does not determine whether an oscillation is a PIO.
8. High-frequency, small-amplitude oscillations in pitch (sometimes referred to as “pitch bobble”), and in roll (“roll ratchet”), may be considered a “mild” form of PIO, and may not even be judged as PIO in all cases. If the amplitudes of the oscillations become intrusive on the piloting task, they are PIOs.
9. PIO that interferes with, but does not prevent, performance of a primary mission task is a “moderate” PIO; if a Cooper-Harper Handling Qualities Rating 7 is obtained, it is usually in the range of 4-6 (Level 2 by handling qualities specifications). In general, “moderate” PIO is associated with peak-to-peak angular rates of less than ±10 degrees/sec and control forces less than ±5 lb.8 “Moderate” PIO requires corrective action for normal operation of the airplane, but if it occurs in developmental testing the flight test program can continue.
10. PIO that prevents performance of the task, or that requires the pilot to abandon the task in an attempt to stop the oscillation, is a “severe” PIO; if a Cooper-Harper Handling Qualities Rating is obtained, it is usually 7 or worse (Level 3 or unflyable by handling qualities specifications). Peak-to-peak angular rates are usually greater than ±10 degrees/sec, and control forces greater than ±10 lb, though rate limiting can attenuate the former and result in large increases in the latter.8 “Severe” PIO requires immediate changes to the airplane, and if it occurs in developmental testing the flight test program should be postponed or redirected until the corrections are made.

5. Four categories of A/RPCs

McRuer [ref. 2] divided A/RPCs into three categories (Cat I, Cat. II and Cat. III) according to the degree of non-linearity of the oscillation of the Pilot-Vehicle System (PVS). Many researchers adopted since then this classification. Figure 8 from ref. 9 presents the classification of these phenomena revealing the general three main A/RPCs categories according to McRuer [ref. 2]. This classification is also illustrative for the rotorcraft case.

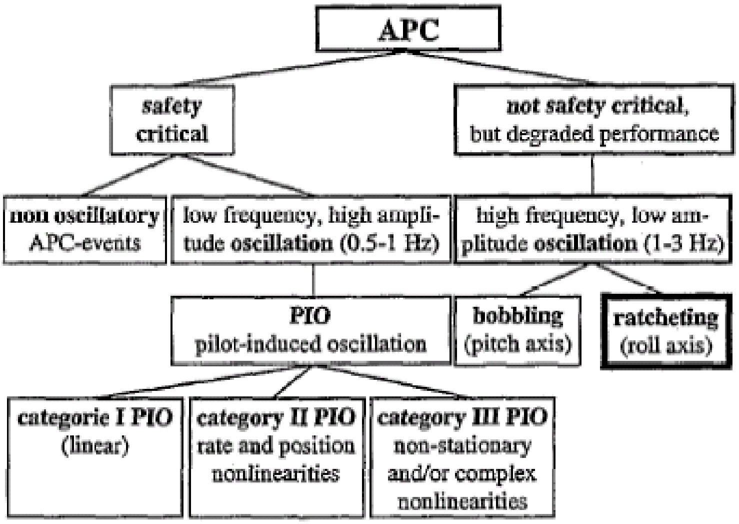


Figure 8 Classification of aircraft/pilot coupling phenomena (for fixed-wing aircraft) [9]

Recently, ref. 10 suggested introducing a 4th category A/RPCs for events that are caused by, or have as a major contributor, structural modes and their interactions with the pilot. These events, also referred to as pilot augmented or assisted oscillations (PAO) in some references, are of special interest for rotorcraft [ref. 11]. The four categories are explained below.

Category I A/RPC - Essentially linear PVS oscillations

A/RPCs in this category are essentially linear and are caused directly by excessive time delays or phase lags in the vehicle dynamics. These are typically caused by digital filtering, an improper aircraft or rotorcraft gain (too sensitive or too sluggish), resulting in overall poor handling qualities. Triggers usually occur during high gain tasks. Those are tasks that require many small pilot corrections and thus increase the pilot workload. Examples of high gain task are the slope landing for rotorcraft or aerial refueling. Typical frequencies of Category I A/RPC are between 0.3Hz and 1.5Hz [2]. A/RPCs in this category are relatively simple to model and best understood. Almost all existing criteria with respect to A/RPC focus on Category I. These types of A/RPCs are least common in during operational flying [2, 13, 14]. An example of an RPC in this category corresponds to the Bo105 RPC presented in Figure 4 and Figure 5.

Category II A/RPC - Quasi-linear PVS oscillations

A/RPCs in this category are quasi-linear events and are triggered by the nonlinear rate and/or position limiting elements (RLEs and/or PLEs). Vehicle dynamics are linear until onset, hence the term quasi-linear. Typical RLEs can be found in digital flight control systems or in actuator dynamics as shown in Figure 9.

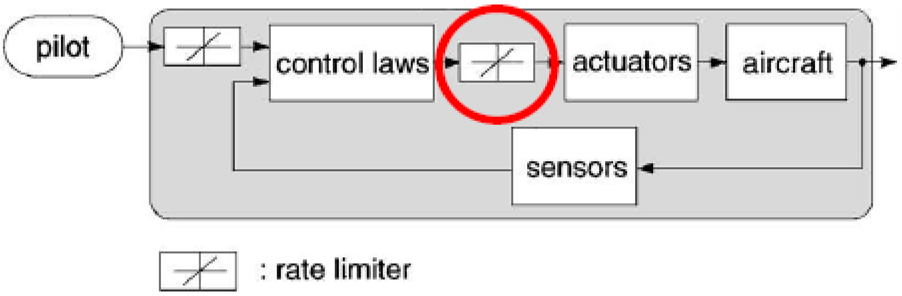


Figure 9 Typical locations of rate limiting elements (taken from [16])

After onset of an RLE (trigger) which is usually caused by a large pilot input, time delays build-up fast, causing the discrepancy between the pilot's input and the intended response to develop quickly. The term "cliff-like" behavior is frequently used [2, 14]. After onset, the phase lag exhibits a jump. This is sometimes referred to as the "jump phenomenon" [15, 16]. This jump is clearly visible in the bode and Nichols plots in Figure 10.

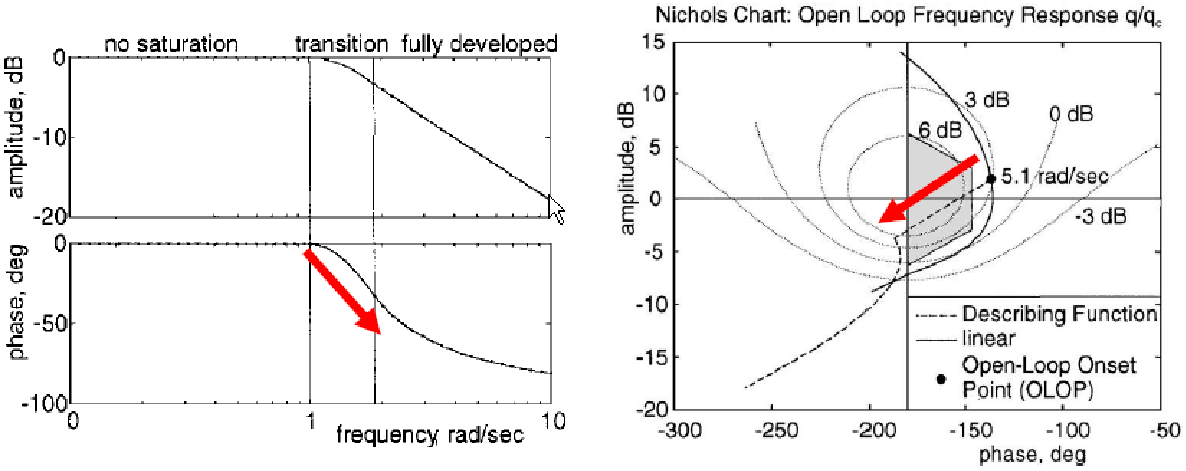


Figure 10: Left: Bode plot indication phase jump after onset; Right: Nichols chart illustrating phase jump after onset (taken from [16])

In the time domain, this building up is visualized in Figure 11. The saw tooth shape is the signature of the rate limiter being active.

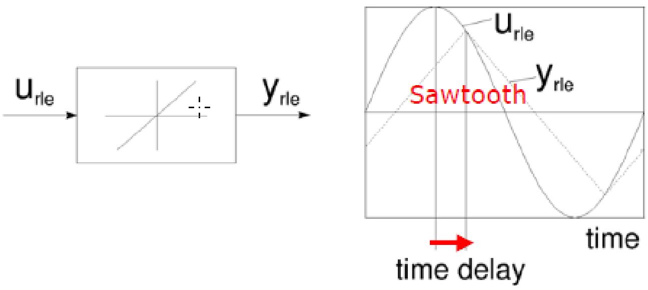


Figure 11: Time delay build-up due to rate limiting (taken from [5])

Although frequencies of the oscillation typically vary for each aircraft or rotorcraft and RLEs, most A/RPC occurrences have a frequency of around 0.5Hz [2, 4, 17]. The relatively new criteria for this category are based on for example the use of a describing function for the non-linear element [18, 19, 21] or the Open Loop Onset Point (OLOP) criterion [20]. Next to being a triggering event, the effects of rate limiting have been at least the cause of sustaining most APC events in the past [2], like in the YF-22 example.

Category III A/RPC - Essentially non-linear PVS oscillations with transitions
A/RPC Events in this category are triggered by mode or task switching or changes in the aerodynamic configurations (for example flaps, gear, etc.) or propulsion system. This switching is non-linear. For example, shifts or transitions in command type of the FCS cause the mental mismatch to develop. In helicopters with FBW and digital control, there have been RPC occurrences when the command type switched from attitude command to rate command in a Weight-on-Wheels situation [22, 23]. The same situation happened for the fixed wing F-8 DFBW (Digital Fly-By-Wire) test aircraft [2] (see Table 1).

Due to the nonlinearities and the fact that dynamics or tasks change, A/RPC occurrences in this category are most difficult to analyze offline [ref. 2]. Criteria specifically designed for this category are practically non-existent. The YF-22 APC case can be included in this category.

Category IV A/RPC - Oscillations due to elastic structural modes or biodynamical couplings

A/RPCs in this category are due to the coupling of elastic structural modes (aero elastic) and the pilot or due to biodynamical couplings. They are the “quicker” type of A/RPC events with frequencies of at least 1Hz [4]. This category includes oscillations with a full attention pilot in the loop or a passive one and as they are caused by an involuntarily or passive interaction between the pilot, typically his limb, and the vibratory motions of the vehicle. The fourth category corresponds also to the so-called biodynamic couplings, involving structural or aeroelastic modes of the aircraft [13, 14].

In case of large transport aircraft, the pilot might excite the aircraft's structural modes and possibly regresses into an A/RPC event. Common in rotorcraft are the couplings between the pilot and the vehicle dynamics with an external slung load [2, 11]. Other examples can be found in [24, 25, 26]. In case of vibration feedthrough to the cockpit and biodynamical couplings, the pilot's body or limbs is shaken, causing passive and involuntary control inputs. A/RPC events of this kind can be called Pilot-Assisted Oscillations or PAO. Especially rotorcraft are prone to these types or RPCs, due to relatively high-amplitude vibratory environment. In ref. 11 an overview of these events with R/C of the US Navy is presented. In ref. 25, a situation is presented where the dynamics of a pilot's arm and the collective handle is coupling with the R/Cs vertical response. The example of the Bo105 RPC event that was shown in Figure 4 and Figure 5 belongs to this category.

Concluding, there are many different kinds of A/RPCs. Thus, when discussing on A/RPCs it is not that there is only one kind of A/RPC that it can happen or not, but, there is a whole range starting from minor but annoying A/RPCs to dangerous A/RPCs. *“To paint all PIOs with a single brush is to run the risk of panicking and rushing to judgment on the basis of a benign, common event, or doing the opposite: trying to whitewash a serious and potentially deadly design flaw.”* [ref. 6]. Therefore, generally, aircraft-pilot couplings can be considered safety-critical and non-safety critical to aircraft operations.

6. Deteriorating factors

Considering the three necessary conditions for A/RPCs of Figure 7 and the interaction between the blocks in the Figure 1 diagram, the following factors can increase A/RPC susceptibility:

1. With respect to the vehicle dynamics:
    a. Long equivalent time delays. This will increase susceptibility directly. This can be inadvertently be achieved by for example excess filtering in the digital FCS.
    b. Complex vehicle configurations with flaps, slats, thrust vectoring etc.

2. With respect to a trigger to occur:
    a. Large number of position limiting elements (PLEs) or rate limiting elements (RLEs). Increasing the number of elements means that onset occurs more frequently or earlier if the limits are small.
    b. Excess or sudden FCS mode or gain shifting. This will trigger mental mismatches more easily.

3. With respect to closed loop control:
    a. A discrepancy in the pilot-vehicle interface. For example, a mistuned control stick (too sensitive) possibly causes closed loop instability.
    b. Added complexity of the control loops. For example pitch attitude control with elevators and thrust vectoring.

7. Fixed wing aircraft versus rotorcraft

Most research mainly focuses on fixed wing APCs. However, rotorcraft are more susceptible to RPC occurrences, since their high-order dynamics play a more important role in RPC development. Figure 12 from ref. 28 presents the generics of an integrated FCS system of a future rotorcraft. One can see the information loop with its display and display laws and also the control loop with its different components like inceptors (manipulators), effectors (actuators and rotor blade controllers), sensors, display and software interfaces (control and display laws). All these have to be ultimately handled and evaluated by the pilot. The problem with rotorcraft is that the additional higher-order dynamics will enter into the final evaluation of the integrated rotorcraft-pilot system.

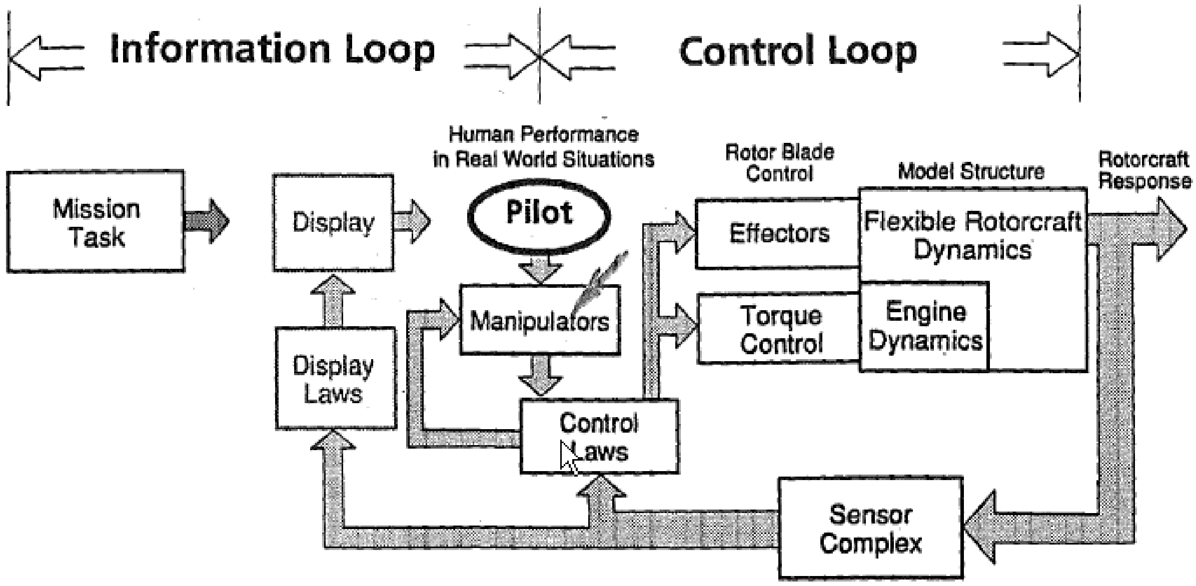


Figure 12: Integrated rotorcraft-pilot system [ref. 28]

The following list unmasks some typical problems for rotorcraft that may induce RPCs:

1. Rotorcraft are inherently dynamically unstable. This means that the vehicle does not stabilize itself and return to a steady flight condition after an upset.
2. There are many couplings resulting from the interactions between the dynamics of the rotating system – the rotor, and the dynamics of the fixed system – the airframe.
3. In conventional fixed-wing aircraft, control moments are transmitted directly from the control surfaces to the aircraft. In contrast, with helicopters, the control inputs are transmitted through the swash plate to the blade pitch, causing the rotor to flap and thence transmitting moments to the aircraft. It is well-known that cyclic inputs are applied at 1/rev-frequency through this swash plate mechanism. Thus, low-frequency pilot inputs generate high-frequency blade excitations. Clearly, rotor blade excitations,

in the form of flap and lag motion, can be transformed back to the fixed airframe system, where eventually a new 1/rev-frequency shift may occur with positive or negative sign. In order to comprehend this transformation mechanism of multi-bladed rotor systems, the concept of rotor modes is helpful: 1) Collective rotor mode dynamics are transferred directly without frequency shift and 2) Cyclic rotor mode dynamics (so-called progressive and regressive modes) are transformed with a ±1/rev frequency shift. This short explanation of the airframe-rotor-airframe transformation behavior characteristic to helicopters is of fundamental importance for understanding rotorcraft RPCs.

4. Based on flight experience with modern helicopters, it appears that the RPCs of special interest are associated mainly with the high-frequency spectrum of structural dynamic and aeroelastic modes. Well-known examples of helicopter RPCs have been related to: 1) excitation of the low - damped main rotor regressive-inplane mode by cyclic inputs resulting in aircraft roll and pitch vibrations 2) excitation of the low frequency pendulum mode of external slung loads by delayed collective and/or cyclic control inputs due to couplings of the load dynamics via elastic cables.
5. In rotorcraft, there exists a high inherent phase lag. This lag is between inceptor input and the response of the vehicle body due to the time required for actuator and rotor responses [refs. 2, 28]. Table 3 [ref. 34] presents the typical equivalent time delays that are the result of implementing a digital FCS in a helicopter.

Table 3 Equivalent time delays for rotorcraft [34]

Element	Delay (ms)	% of total
Rotor	66	30
Actuators	31	14
Control laws	17	8
Computations	22	10
Notch filter	11	5
Stick dynamics and filtering	76	34
Total delay	223	

One can see that the rotor accounts for most of the equivalent time delays (66 ms). This delay of 66 ms is not present in control loops in fixed wing aircraft. The delay typically amounts to about 100ms with conventional flight controls (actuators included). With FBW and filtering, the total delay can amount to 250ms [ref. 35]. Figure 13 [from ref. 38] illustrates what happens to the phase lag of the helicopter dynamic response if the time delay is increased. The figure presents the bode plot for the pitch response to a swash plate (control) deflection in (note that time delays don't influence the magnitude plot). Looking at this figure, two observations can be made: 1) The slope becomes steeper. This so-called phase roll-off or rate at 180 deg crossover frequency increases the equivalent time delay and 2) And the phase bandwidth (crossover frequency at 135 deg) decreases. The combined effect of these two trends is that, due to the larger decrease in rate of the phase lag at a lower frequency, the phase margin decreases quicker for increasing input frequencies. In other words, the system destabilizes earlier.

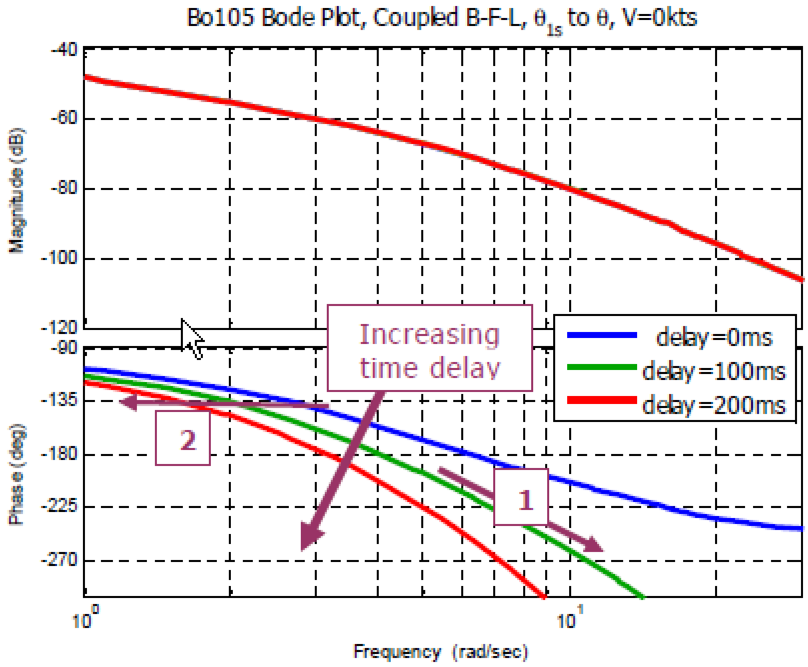


Figure 13: Effects of increasing the time delay on phase lag for a Bo-105 helicopter

6. Cross coupling of the control inputs and off-axis responses in rotorcraft have a negative impact on handling qualities, thus increasing pilot workload [36, 37].
7. There are potential couplings between the dynamics of rotorcraft and external underslung loads, increasing complexity even further [11].
8. The flight deck in rotorcraft is a highly vibrating environment, which causes biodynamic couplings to be more prevalent [25, 11].

8. Conclusions

The present report intends to solve the **Key Problem #1** of the ARISTOTEL project, i.e.: In current design practice there is a general need to understand what exactly a A/RPC is and how it manifests. Based on the previous analysis of what an A/RPC is and what are its characteristics, the following definition is proposed:

An aircraft- or rotorcraft-pilot coupling (A/RPC) is an unintentional (inadvertent) sustained or uncontrollable vehicle oscillations characterized by a mismatch between the pilot's mental model of the vehicle dynamics and the actual vehicle dynamics. The result is that the pilot's control input is out-of-phase with the response of the vehicle, possibly causing a diverging motion.

The proposed term with respect to the definition above is "*mental mismatch*" which is, key to identifying and analyzing A/RPCs as such. It can also be said that in normal situation, the pilot drives the vehicle, whereas during an A/RPC event the situation is reversed. In that case, the pilot is driven by the vehicle due to this mental mismatch and actively tries to control it [ref. 6]. Due to the stronger formulated definition, some events such as ballooning during a landing approach or a hovering task of an inexperienced pilot cannot be considered to be A/RPCs by the definition above. However, such events can become A/RPCs when the vehicle starts driving the pilot. Note the two precepts that are needed for A/RPCs definition: 1) oscillatory characteristics; and 2) out-of-phase behaviour.

9. References

1. McFarland, M.W., *The Papers of Wilbur and Orville Wright*, 1st Ed., McGraw Hill, New York, 1953.
2. McRuer, D.T., et al., "AVIATION SAFETY AND PILOT CONTROL. Understanding and Preventing Unfavorable Pilot-Vehicle Interactions", *ASEB National Research Council*, National Academy Press, Washington D.C., 1997.
3. AGARD, "AGARD Flight Mechanics Panel on Handling Qualities of Unstable Highly Augmented Aircraft", *AGARD AR-279*, May, 1991.
4. McKay, K., "Pilot Induced Oscillation – A Report on the AGARD Workshop on PIO, 13th May, 1994", *AGARD CP-560*.
5. AGARD,, "AGARD Flight Vehicle Panel Workshop Pilot Induced Oscillations", *AGARD-AR-335*, Feb. 1995
6. Mitchell, D.G., Klyde, D.H., "Identifying a PIO Signature – New Techniques Applied to an Old Problem", AIAA 2006-6495 presented at the *AIAA Atmospheric Flight Mechanics Conference and Exhibit*, 21-24 August 2006, Keystone, Colorado.
7. Anon, "Flight Control Design – Best Practices", RTO-TR-029, RTO/NATO report, Dec. 2000
8. Mitchell, D.G., et. al., (2004), "Evolution, Revolution and Challenges of Handling Qualities", *Journal of Guidance, Control and Dynamics, 27(1), 2004, pp. 12-28*
9. Höhne, G., "A Biomechanical Pilot Model for Prediction of Roll Racketing", *Proceedings of the AIAA Conference on Guidance, Navigation and Control, AIAA paper 1999-4092,* 1999, pp. 187-196.
10. Klyde, D.H., Mitchell, D.G., "A PIO Case Study – Lessons Learned through Analysis", *AIAA Atmospheric Flight Mechanics Conference and Exhibit*, San Francisco, August 15-18, 2005.
11. Walden, R., Barry, "A Retrospective Survey of Pilot-Structural Coupling Instabilities in Naval Rotorcraft", *63rd Annual Forum of the American Helicopter Society, Virginia Beach, VA, May 1-3, 2007*
12. "Department of Defense Interface Standard, Flying Qualities of Piloted Aircraft," MIL-STD-1797A, Jan. 1990; Notice of Change, 28 June 1995.
13. Klyde, D.H., Mitchell, D.G., Investigating the Role of Rate Limiting in Pilot-Induced Oscillations, Journal of Guidance, Control, and Dynamics 27 (5), 2004, pp. 804-813.
14. D.G. Mitchell, D.H. Klyde, Recommended Practices for Exposing Pilot-Induced Oscillations or Tendencies in the Development Process, USAF Developmental Test and Evaluation Summit, American Institute of Aeronautics and Astronautics, Woodland Hills, CA, 2004
15. H. Duda, Effects of rate limiting elements in flight control systems - A new PIO-criterion, AIAA Guidance, Navigation and Control Conference, Baltimore, Washington, DC: American Institute of Aeronautics and Astronautics, United States, 1995
16. H. Duda, Prediction of pilot-in-the-loop oscillations due to rate saturation, Journal of Guidance, Control, and Dynamics 20 (3) (1997) 581-587.
17. Anon., Flight control design: best practices, in: N.A.T. Organisation (Ed.), STAR. Vol. 39, 2001.
18. D.H. Klyde, D.T. McRuer, T.T. Myers, Pilot-induced oscillation analysis and prediction with actuator rate limiting, Journal of Guidance, Control, and Dynamics 20 (1) (1997) 81-89.

19. D.H. Klyde, D.T. McRuer, T.T. Myers, PIO analysis with actuator rate limiting, AIAA Atmospheric Flight Mechanics Conference, San Diego, Reston, VA: American Institute of Aeronautics and Astronautics, United States, 1996.
20. H. Duda, G. Duus, New handling qualities database on PIO due to rate saturation, Cologne, Germany: Deutsches Zentrum fuer Luft und Raumfahrt (1997)
21. F. Amato, R. Iervolino, S. Scala, L. Verde, New criteria for the analysis of PIO based on robust stability methods, AIAA Atmospheric Flight Mechanics Conference and Exhibit, Portland, Reston, VA: American Institute of Aeronautics and Astronautics, United States, 1999.
22. C.J. Bauer, A landing and takeoff control law for unique-trim, fly-by-wire rotorcraft flight control systems, European Rotorcraft Forum, 19th, Como, Amsterdam, Netherlands: National Aerospace Laboratory, Netherlands, 1993.
23. R.L. Stiles, J. Mayo, A.L. Freisner, K.H. Landis, B.D. Kothmann, Impossible to Resist: The Development of Rotorcraft Fly-by-Wire Technology, Proceedings of the 60th annual forum of the American Helicopter Society (2004) 1-18.
24. G. Hoehne, Roll ratcheting - Cause and analysis, Deutsches Zentrum fuer Luft und Raumfahrt. Forschungsberichte. (2001).
25. J. Mayo, The involuntary participation of a human pilot in a helicopter collective control loop,European Rotorcraft Forum, 15th, Amsterdam, Netherlands, 1989.
26. D.L. Raney, E.B. Jackson, C.S. Buttrill, W.M. Adams, The impact of structural vibration on flying qualities of a supersonic transport, AIAA Atmospheric Flight Mechanics Conference and Exhibit, Montreal, United States, 2001.
27. J.J. Harris, G.T. Black, F-22 control law development and flying qualities, AIAA Atmospheric Flight Mechanics Conference, San Diego, Reston, VA: American Institute of Aeronautics and Astronautics, United States, 1996.
28. Hamel, Peter, G., “Rotorcraft-Pilot Coupling – A Critical Issue for Highly Augmented Helicopters?”, paper no. 21, AGARD-FVP Symposium “Advances in Rotorcraft Technology, 27-30 May 1996, Ottawa, Canada
29. C. Ockier, Pilot-Induced Oscillations in Helicopters - Three Case Studies, Report No. IB 111-96/12, DLR Institut fur Flugmechanik, Braunschweig, Germany, 1996.
30. Smith, Ralphh, “Observations on PIO”, AGARD Flight Vehicle Integration Panel Workshop on Pilot Induced Oscillations, 1995
31. Lawrence, Ben, Padfield, Gareth, D., “A handling qualities analysis of the Wright brothers 1902 Glider, AIAA Atmospheric Flight Mechanics”, Conference, Austin, Texas, 11-14 August, 2003.
32. H. Duda, Prediction of pilot-in-the-loop oscillations due to rate saturation, Journal of Guidance, Control, and Dynamics 20 (3) (1997) 581-587.
33. H. Duda, G. Duus, G. Hovmark, L. Forssell, New flight simulator experiments on pilot involved oscillations due to rate saturation, Journal of Guidance, Control, and Dynamics. Vol. 23, Nr 2, 2000 , pp.. 312-318
34. M. Tischler, System identification requirements for high-bandwidth rotorcraft flight control system design, Journal of Guidance, Control, and Dynamics 13, 1990, pp. 835-841.
35. M. Tischler, J. Fletcher, P. Morris, G. Tucker, Flying quality analysis and flight evaluation of a highly augmented combat rotorcraft, Journal of Guidance, Control, and Dynamics 14, 1991, pp. 954-963.
36. C.J. Ockier, Flight evaluation of the new handling qualities criteria using the BO 105, AHS, Annual Forum, 49th, Saint Louis, Alexandria, VA: American Helicopter Society, United States, 1993
37. C.J. Ockier, H.-J.r. Pausder, C.L. Blanken, An investigation of the effects of pitch-roll (de)- coupling on helicopter handling qualities, Deutsche Forschungsanstalt fur Luft- und Raumfahrt, Koln, 1995.
38. GARTEUR Helicopters AG-16 “Rigid body and aeroelastic rotorcraft-pilot coupling – prediction tools and means of prevention” https://exsites.dlr.de/ft/garteurag16

39. McRuer, D.T., “Pilot-Induced Oscillations and Human Dynamic Behavior”, *NASA CP-4683*, NASA, July 1995.
40. Pearcy, Arthur, "Flying the Frontiers -- NACA and NASA Experimental Aircraft," Naval Institute Press, Annapolis, Maryland, 1993.
41. Finch, Thomas W., and Gene J. Matranga, Launch, Low-Speed, and Landing Characteristics Determined from the First Flight of the North American X-15 Research Airplane, NASA TM X-195, Sept. 1959.
42. Matranga, Gene J., Analysis of X- 15 Landing Approach and Flare Characteristics Determined from the First 30 Flights, NASA TN D-1057, July 1961.
43. Smith, John W., and Donald T. Berry, Analysis of Longitudinal Pilot-Induced Oscillation Tendencies of YF-12 Aircraft, NASA TN D-7900, Feb. 1975.
44. Smith, R.H. A Theory for Longitudinal Short-Period Pilot-Induced Oscillations, AFFDL-TR-77-57,June 1977.\
45. Powers, Bruce G., "An Adaptive Stick-Gain to Reduce Pilot-Induced Oscillation Tendencies," J. Guidance, Control, and Dynamics, Vol. 5, Mar.-Apr. 1982, pp. 138-142.
46. Ashkenas, I.L., R.H. Hoh, and G.L. Teper, "Analysis of Shuttle Orbiter Approach and Landing," J. Guidance, Control, and Dynamics, Vol. 6, No. 6, Nov.-Dec. 1983, pp. 448-455.
47. Dornheim, Michael A., "Report Pinpoints Factors Leading to YF-22 Crash," Aviation Week and Space Technology, 9 Nov. 1992, pp. 53-54.
48. Aircraft Accident Report PB 93-910408, National Transportation Safety Board, NTSB/AAR-93/07;Washington, DC, 27 Oct. 1993.
49. Crawford C. Charles, and Jones P. Seigler, KC-135A Stability and Control Test, Air Force Flight Test Center TR 58-13, May 1958.
50. Simmons, Carl D., and Donald M. Sorlie, F-101B Air Force Stability and Control Evaluation, Air Force Flight Test Center, TR 58-11, May 1958.
51. Pearcy, Arthur, "Flying the Frontiers -- NACA and NASA Experimental Aircraft," Naval Institute Press, Annapolis, Maryland, 1993.
52. Kempel, Robert W., Analysis of a Coupled Roll-Spiral Mode. Pilot-Induced Oscillation Experienced with the Af2-F2 Lifting Body, NASA TN D-6496, Sept. 1971.
53. Smith, Ralph H., Notes on Lateral-Directional Pilot-Induced Oscillations, AFWAL TR-81-3090, Mar. 1982.
54. Smith, John W., Analysis of a Lateral Pilot-Induced Oscillation Experienced on the First Flight of the YF-16 Aircraft, NASA TM 72867, Sept. 1979.
55. Abzug, M.J. and H.B. Dietrick, Interim Report on Elimination of Pilot-Induced Oscillations from the Douglas Model A4D-2 Airplane, Report ES26613, Douglas Aircraft Company, 20 Mar. 1957.
56. Terrill, W.H., L.R. Springer, and J.G. Wong, Investigation of Pilot-Induced Longitudinal Oscillation in the Douglas Model A4D-2 Airplane, Douglas Aircraft Company, Inc., Report LB-25452, 15 May 1957.
57. Smith, R.H. A Theory for Longitudinal Short-Period Pilot-Induced Oscillations, AFFDL-TR-77-57, June 1977.
58. Ashkenas I.L., H.R. Jex, and D.T. McRuer, Pilot-Induced Oscillations: Their Causes and Analysis, Northrop-Norair Rept., NOR 64-143, June 1964.
59. Jex, H.R., Summary ofT-38A PIO Analysis, Systems Technology, Inc., TR-239-1, Jan. 1963.
60. Levi, O.A. and W.E. Nelson, "An Analytical and Flight Test Approach to the Reduction of Pilot Induced Oscillation Susceptibility," July-Aug. 1964, pp. 178-184.
61. Hirsch, D. and R. McCormick, "Experimental Investigation of Pilot Dynamics in a Pilot-Induced Oscillation Situation", Nov.-Dee. 1966.
62. Chalk, C.R., Another Study of the T-38A PIO Incident, Calspan Advanced Technology Center, FRM 534, 31 Aug. 1978.

63. Norton, William J., Captain, USAF, "Aeroelastic Pilot-in-the-Loop Oscillations," presented at PIO Workshop following Active Control Technology: Applications and Lessons Learned, AGARD, Turin, Italy, May 1994.
64. Parham, Tom, Jr., David Popelka, David G. Miller, and Arnold T. Froebel, "V-22 Pilot-in the-Loop Aeroelastic Stability Analysis," American Helicopter Society, 47th Annual Forum Proceedings, May 1991
65. Jex, H. R., “Problems in Modeling Man-Machine Control Behavior in Biodynamic Environments”, NASA CP-281, pp. 3-13, 1971
66. Aponso, B. L. ,et al.,” Identification of Higher-Order Helicopter Dynamics using Linear Modeling Methods"' 47 th Annual Forum, AHS, Phoenix, May 6-8, 1991, pp. 137-153
67. Buchacker, E., “Experience with SIFT Flight-Test-Techniques at the German Air Force Flight Test Center “AGARD-CP-333, Paper 24, June 1982
68. Tischler, M. B., et al., “Flying Quality Analysis and Flight Evaluation of Highly Augmented Combat Rotorcraft”, AIAA J. Guidance, Vol. 14, No. 5, pp. 954-963, Sep.-Oct. 19
69. Pausder, H. J., “Investigation of the Effects of Bandwidth and et al. Time Delay on Helicopter Roll-Axis Handling Qualities”. NASA CP-3220, Jan. 1993
70. Berry, Donald T., Bruce G. Powers, Kenneth J. Szalai, and R.J. Wilson, "In-Flight Evaluation of Control System Pure Time Delays," Journal of Aircraft, Vol 19, No 4, Apr. 1982, pp 318-323.
71. Johnson, Donald E. and Raymond E. Magdaleno,” Independent Assessment of C/MH-53E Technical Evaluation Program (TEP)”, Systems Technology, Inc. TR-1251-1 R, Sept. 1990.
72. Russian Journal “Aviation Science and Technology” no.2(490), 1991
73. Padfield, Gareth, D., Helicopter Flight Dynamics”, Blackwell Science LTD., 1996
74. Crash of Convair B-58 Bomber, JOURNEY IN AERONAUTICAL RESEARCH: A Career at NASA Langley Research Center, Monographs in Aerospace History, Number 12, 1960.
75. D. H. Klyde, T. T. Myers, R. E. Magdaleno, and J. G. Reinsberg, Identification of the Dominant Ground Handling Characteristics of a Navy Jet Trainer, Journal of Guidance, Control, and Dynamics, Vol. 25, No. 3, pp. 546-552, 2002
76. Kendall, E. R., “The Design and Development of Flying Qualities for the C-17 Military Transport Airplane,” in Advances in Aircraft Flight Control, Tischler, M. B., ed., Taylor & Francis, PA, 1996.

10. List of Abbreviations

ARISTOTEL = Aircraft and Rotorcraft Pilot Couplings – Tools and Techniques for Alleviation and Detection
APC = Aircraft Pilot Coupling
RPC = Rotorcraft Pilot Coupling
CSAS = Control and Stability Augmentation System
PIO = Pilot Induced Oscillations
PAO = Pilot Assisted Oscillations
FCS = Flight Control System
FBW = Flight by Wire
DFBW = Digital Flight by Wire
HQR = Handling Qualities Rating
PLE = Position Limiting Element
RLE = Rate Limiting Element