Present and Future Trends in Rotorcraft Pilot Couplings (RPCs) – *A Retrospective Survey of Recent Research Activities within the European project ARISTOTEL*

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Abstract: Fixed and rotary wing pilots alike are familiar with potential instabilities or with annoying limit cycle oscillations that arise from the effort of controlling aircraft with high response actuation systems. Understanding, predicting and supressing these inadvertent and sustained aircraft oscillations, known as Aircraft (Rotorcraft)-Pilot Couplings (A/RPCs) is a challenging problem for the designers. Recent experiences show that especially modern designs are being confronted with an increasing degree of dangerous A/RPCs. The reason for this is that modern aircraft feature a significant level of automation in their Flight-Control-Systems (FCS). FCS is generally intended to relieve pilot workload and allow operations in degraded weather and visibility conditions. Especially in the modern rotorcraft, there seem to be embedded tendencies predisposing the FCS system towards dangerous RPCs. As the level of automation is likely to increase in future designs, extending to smaller aircraft and to different kinds of operation, the consequences of the pilot 'fighting' the FCS system and inducing A/RPCs needs to be eradicated. In Europe, the ARISTOTEL project (2010 – 2013) has been launched with the aim of understanding and predicting modern aircraft's susceptibility to A/RPC. The present paper gives an overview of the current status in RPCs and what can be expected in future designs.

Nomenclature

ACAH	Attitude command/Attitude Hold
ACARE	Advisory Council for Aeronautic Research in Europe
ADOCS	Advanced Digital/Optical Control System
AFCS	Automatic Flight Control System
A/RPC	Aircraft (Rotorcraft)-Pilot Coupling
ARTI	Advanced Rotorcraft Technology Integration
ATTHeS	Advanced Technologies Testing Helicopter System
DFBW	Digital Fly-by-Wire
EMS	Emergency Medical Services
FCS	Flight Control System
HHC	Higher Harmonic Control
IBC	Individual Blade Control
OLOP	Open Loop Onset Point
NoE	Nap of the Earth
PIO/PAO	Pilot Induced (Assisted) Oscillations
PVS	Pilot-Vehicle-System
RLEs/PLEs	Rate/Position Limiting Elements
SAS/SCAS	Stability and (Control) Augmentation System
VNE	Never Exceed Speed

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INTRODUCTION

Today's high performance rotorcraft are a product of the ever increasing demands of operator requirements. They are faster and more capable, but are consequently more complex than their predecessors. As their complexity increases, it appears that both, engineers and pilots must be prepared to deal with an associated increased incidence of unfavourable so-called "**Aircraft-and-Rotorcraft Pilot Couplings**" **(A/RPC)**. Generally, A/RPCs are oscillations or divergent vehicle responses originating from adverse pilot-vehicle couplings. These undesirable couplings can range in severity from benign to catastrophic; benign A/RPCs affect the operational effectiveness of a mission, degrading the aircraft handling qualities; catastrophic A/RPCs result in the loss of the aircraft and lives. Until 1995, A/RPCs were usually known under the name of Pilot Induced/Pilot Assisted oscillations or Pilot in-the loop/Pilot-out-of-the-loop oscillations (PIO/PAO). The reason for this was that, in the past, the key causal factor in A/RPCs appeared to be the pilot and the word 'Pilot Induced Oscillations (PIOs)' considered that he/she was mainly responsible for any such issue. Generally, for modern aircraft, it has become increasingly clear that the pilot is not at fault and that it actually is the rapid advance in the field of Flight-Control-Systems (FCS) that has increased the sensitivity of the pilot-vehicle system to the appearance of unfavourable A/RPC events. "*As a matter of fact, almost every aircraft equipped with a partial or total fly-by-wire FCS has, at one time or another of development process, experienced one or more A/RPC events*" [ref. 1]. In other words, in the FCS of any modern aircraft, there seems to be some embedded tendencies that predispose the pilot-aircraft system towards A/RPC occurrence.

Recently, the European Commission launched, under the umbrella of the 7th Framework Programme (FP7), the ARISTOTEL project (Aircraft and Rotorcraft Pilot Couplings – Tools and Techniques for Alleviation and Detection www.aristotel-project.eu), the aim of which is to advance the state-of-the-art of A/RPC prediction and suppression. With a duration of 3 years, starting from October 2010, and involving partners from across Europe – Delft University (TUD) as coordinator and NLR from The Netherlands, ONERA from France, Politecnico di Milano (POLIMI) and Università Roma Tre (UROMA3) from Italy, University of Liverpool (UoL) from the UK, STRAERO from Romania, PZL-Swidnik from Poland, TsAGI from Russia and EURICE from Germany. The ARISTOTEL project's objectives are to improve the physical understanding of present and future A/RPCs and to define criteria to quantify an aircraft's susceptibility to A/RPC. ARISTOTEL project is mainly based on the experience of previous European GARTEUR projects related to the area of A/RPCs (i.e. GARTEUR FM-AG12 "Pilot-in-the-Loop-Oscillations - analysis and test techniques for their prevention, phase I" (1999-2001) [ref. 2], GARTEUR FM-AG15 "Pilot-in-the-Loop-Oscillations - analysis and test techniques for their prevention, phase II" (2004-2007) [ref. 3] and GARTEUR HC-AG16 "Rigid body and aeroelastic rotorcraft-pilot coupling – prediction tools and means of prevention" (2005-2008) [ref. 4, 5, 6, 7] and is advised by main helicopter manufacturers in Europe such as EUROCOPTER and AGUSTA-WESTLAND.

ARISTOTEL considers also the findings of the excellent work performed between 1995 and 1996 in the United States by the US NRC/ASEB Study Committee under the leadership of D.T. Mc.Ruer [ref. 1], one of the broadest and most well documented open literature investigations especially on APC problems. Further, the workshops organised on APC problems by the NATO Nations under the AGARD Flight Vehicle Integration Panel, Work Group 17 "*Flying Qualities of Unstable Highly Augmented Aircraft*" (1991) [ref. 8], Flight Vehicle Panel Workshop on "Active Control Technology" (1995) [ref. 9] and "*Pilot Induced Oscillations*" (1995) [ref. 10], NASA research conducted in (1995) [refs. 11] and 2001 [ref 12] and the research of the US Air Force [ref. 13] were also analysed by ARISTOTELians. The present paper is a synthesis of initial ARISTOTEL's investigations in the area of RPCs.

DEFINING AND UNDERSTANDING A/RPCs

The first dilemma that one needs to solve when analysing aircraft oscillatory behaviour is whether or not a particular event is an A/RPC. According to [ref. 14], ten different definitions seem to exist in the open literature and many times the aerospace community is unable to agree upon whether or not a particular event is an A/RPC. Also, it has been argued by some experts that renaming of PIO/PAOs as APCs in the case of aircraft or RPCs in the rotorcraft case is even more confusing. "*The introduction of the term "Aircraft-Pilot Coupling" (APC, or sometimes APC) in the mid-1990's contributed to the obscuration of the obvious: while the intent of this new term was to capture both oscillatory and non-oscillatory adverse behaviors of the aircraft-pilot system, 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. 14]. Presently, PIO/PAO are considered subclasses of A/RPCs.

In this context, the basic definitions of the old terminology PIO/PAO for an A/RPC event must be reminded. PIOs (Pilot Induced Oscillations) occur when the pilot inadvertently causes divergent oscillations by applying control inputs which are essentially in the wrong direction, or have a significant phase lag with respect to the aircraft/rotorcraft response. High gain tasks, long time delays introduced by the pilot while controlling the aircraft or changes in the pilot control behaviour introduced by FCS and control interfaces can all be the cause of a PIO.

PAO -Pilot Assisted Oscillations - are higher frequency phenomenon related to involuntary control inputs given from the pilot, which may destabilize the aircraft.

Figure 1 presents the closed loop Pilot-Vehicle System (PVS) for a modern rotorcraft. The input into the system is the **Mission Task**. This can be anything from a tracking task, manoeuvre or forcing on the stick. **The pilot uses** the task to control the integrated **Rotorcraft system** which comprises **Inceptors** (manipulators), **Effectors** (actuators controlling the vehicle control surfaces, i.e. blade pitching system in the case of rotorcraft), **Sensors, Displays, Software interfaces - Control laws** in the form of SAS, SCAS (Stability and Control Augmentation System) , digital filters of a Flight Control System etc., and **Display laws**) and the inherent R**otorcraft dynamics** where the dynamics of the vehicle is located. The output of the rotorcraft system is fed back to the pilot and its various automatic systems. The **Pilot** is of course the essential element in the PVS; he is the one that ultimately has to handle and evaluate all the complex vehicle systems.

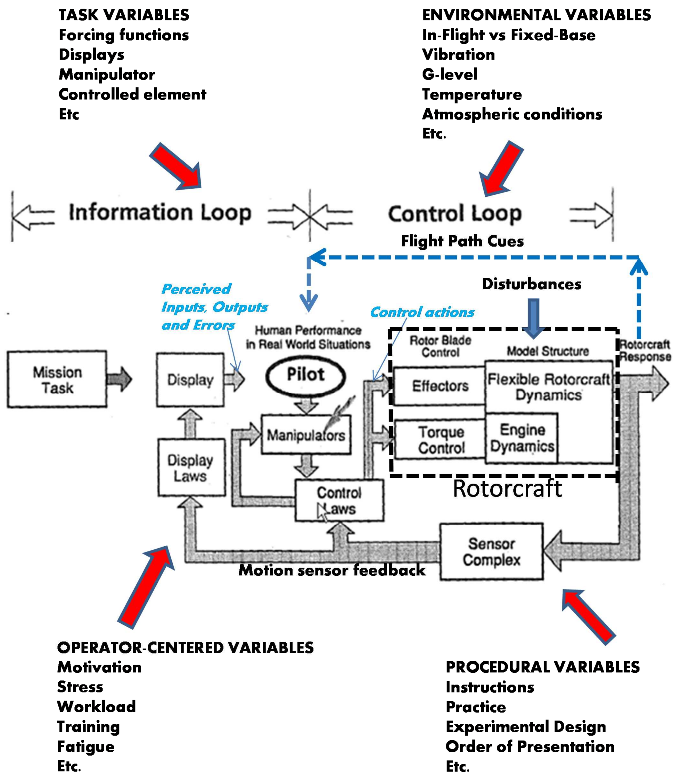

Figure 1 Pilot in the loop system for RPC analysis [adapted from ref. 21]

In order to understand all possible factors that come into play during a RPC event, Figure 1 added four types of variable which, according to McRuer and Jex [ref. 20], affect pilot decisions. These are:

- **Task variables**: Comprise all the system inputs and control system elements external to the pilot and which enter directly and explicitly into the pilot's control task. Four of these -forcing function, display, manipulator, and controlled element dynamics – have a major effect on the pilot dynamics.
- **Environmental variables** are the variables external to the pilot such as ambient illumination, temperature, vibration, and G-loading (to the extent that this is superimposed on, rather than controlled by the pilot).
- **Operator-centred variables**. These include such things as training, fatigue, and motivation.
- **Procedural variables** (for a given experimental series) include such things as instructions, practice, order of presentation, etc., which can be very important to the accuracy and generality of experimentally based conclusions.

A closer look to Figure 1 reveals typical problems for rotorcraft that may induce RPCs:

1. In Key flight conditions, rotorcraft are inherently dynamically unstable, i.e. the vehicle does not stabilize itself and return to a steady flight condition after an upset. Moreover, rotorcraft are often required to execute demanding manoeuvres such as precision landings, hovering (with or without slung-loads), tracking tasks or autorotation. All these missions are definable as high-gain tasks.
2. Rotorcraft are prone to vibrations transmitted from the rotors/prop-rotors to the airframe. The vibrations are generated by the inherent nature of the rotating-blade transmitting periodic loads to the hub fixed frame, and also by the aerodynamic interferences between the rotor and the fuselage. Once in the cabin, vibrations can afflict the pilot resulting in wrong command inputs or biodynamic coupling (unaware inputs).
3. Rotorcraft are characterized by many control couplings resulting from the interactions between the dynamics of the rotating system – the rotor, and the dynamics of the fixed system – the airframe.
4. In conventional fixed-wing aircraft, control moments are transmitted directly from the control surfaces to the aircraft. In contrast, in rotorcraft, the control inputs are transmitted through the swashplate 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 the swashplate 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 airframe-rotor transformation mechanism of multiblade rotor systems, the concept of rotor modes is helpful. For example, collective rotor mode dynamics are transferred directly without frequency shift and cyclic rotor mode dynamics (so-called progressive and regressive modes) are transformed with a ±1/rev frequency shift. Based on flight experience with modern helicopters, it appears that the RPCs of special interest are associated mainly with the multiblade rotor frequencies. For example, excitation of the low-damped main rotor regressive-inplane mode by cyclic inputs results in aircraft roll and pitch vibrations, or in the 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 between inceptor input and vehicle body response due to the time required for actuator and rotor responses. Table 1 from ref. 22 presents the typical equivalent time delays that are the result of implementing a digital FCS in a helicopter (see also Figure 4). One can see that the rotorcraft accounts for total effective time delays of more than 200 ms resulting from 50-70 ms inherent rotor response delays (66ms in the Table 1), as rotor flapping responds to pitch input with about 90 deg phase delay, which corresponds to a quarter of the rotor period and time constant $\tau = \frac{\pi}{2\Omega}$ (s), some 30 ms actuator delay and additional delays due to digital computing, sensor signal shaping and filtering. This rotor inherent delay 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 rotorcraft delay can amount to 250ms [ref. 23]. The total effective time delay of the rotorcraft-pilot system is directly related to the higher-order dynamics of actively controlled rotorcraft and will result in reduced system bandwidth and increased system phase delay. System bandwidth and effective time delay are two of the most important flight control design and specification parameters of the US Army's rotorcraft handling Qualities Requirements Standard, ADS-33D [ref. 26]. Figure 2 from ref. 5 illustrates what happens to the phase lag of the helicopter dynamic response when the time delay is increased. The figure presents the bode plot for the pitch response to a swashplate (control) deflection input (note that time delays do not influence the magnitude plot). Looking at this figure, two observations can be made: a) the slope becomes steeper. This so-called phase roll-off or rate at 180 deg crossover frequency increases the equivalent time delay and b) 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. Concluding, total effective time delays of more than 200 ms, may reveal poor handling qualities due to high gain tasks. Such time delays can be a strong cause of mental mismatch for the pilot with vehicles' dynamics.

Table 1 Equivalent time delays for rotorcraft [ref. 22]

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	

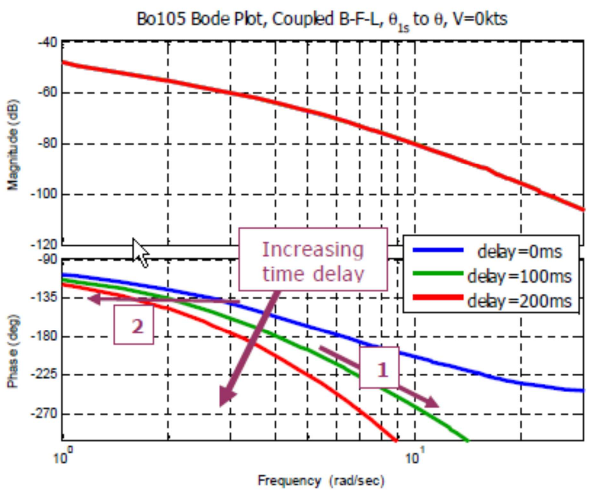

Figure 2 Effects of increasing the time delay on phase lag for a Bo-105 helicopter [from ref. 5]

Following Figure 1, the first goal of the ARISTOTEL project was to give a unified definition on A/RPCs to be used throughout the project. "*This is the best way to be sure that we are all talking about the same phenomenon, even if there is wide variation in the details of its causes and characteristics*"[ref. 14]. In ARISTOTEL, an exhaustive review of the history of the studies related to A/RPC was performed, together with an analysis of the involved literature. A database of accidents occurred in the last 60 years both regarding APC and RPC was then put together (see Appendix A).

The following definition was then proposed to be used throughout the project:

> *"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."*

This definition is the result of an exhaustive discussion between the project partners where every single word has been given the right weight in order not to judge too severely or too negligently the risk of actual A/RPC happening. Three keywords can be highlighted from this definition, which can be found in almost every RPC accident:

- **Oscillatory behaviour**: every RPC event is related to oscillatory behaviour perceived (and then induced) by the pilot. If not leading to crash and catastrophic consequences, these events are related to extreme discomfort and are reported as dangerous happenings.
- **Mental Mismatch**: is always related to RPC in that the pilot shows a wrong mental model of the dynamics of the system he/she is leading/lagging and increasing levels of unawareness of the command input he/she is giving. One can see that both descriptions of PIO and PAO as given above can be related to mental mismatch, leading to either a wrong command input in the PIO or to a totally unaware command input in the case of PAO.
- **Out-of-phase behaviour**: every fully developed A/RPC reports an out-of-phase input-output response witnessing the vehicle loss of control.

As discussed by McRuer [ref. 1], there are three crucial ingredients in an A/RPC event: 1) a change in pilot behaviour in his/her closed-loop control of the aircraft, 2) a change in the dynamic state or configuration of the aircraft and 3) an initiation mechanism commonly referred to as 'trigger'. Figure 3 presents the necessary and sufficient condition for A/RPC development. 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 behaviour of the vehicle, etc. (endogenous trigger) [refs. 1, 8, 56]. Trigger events may lead to A/RPC, however, not all trigger events will necessarily develop into A/RPC. Figure 3 from [ref. 57] shows that A/RPCs occur because aircraft dynamics allows them. For A/RPC to occur, aircraft must respond to pilot inputs in a manner that propagates them.

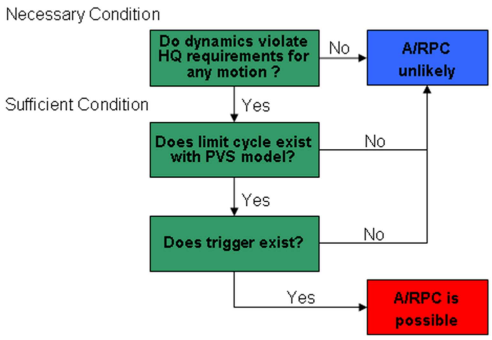

Figure 3 Three necessary conditions for A.RPCs [ref. 57]

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, as stated earlier, the aircraft must respond to the pilot's input in a manner that propagates an A/RPC. Aircraft characteristics that are known to facilitate A/RPC behaviour include sluggish response modes, lightly damped modes, excessive phase lag or time delay, sensitive stick gradient, unusual coupling responses, and unstable modes [ref. 58].

> *Trigger = 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 corrective control.*

There are considered three classes of triggers according to [2]: environmental triggers, vehicle triggers and pilot triggers. The environmental and pilot triggers have historically been found to be the most frequent. However, for modern configurations, vehicle triggers have become also a threat for vehicle's safety.

A SHORT HISTORY OF ROTORCRAFT PILOT COUPLINGS WITH A RECENT DATABASE OF EVENTS

Adverse A/RPC problems have manifested themselves since the early days of manned flight. The earliest recorded examples of PIOs date back to the Wright Brothers first aircraft [refs. 1, 15]. According to ref. 9, 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 A/RPCs continue to occur.

In order to better understand the incidence and the nature of A/RPCs, a database of A/RPCs cases was collected and updated from open literature, along with accidents investigation reports of the National Transportation Safety Board (NTSB) and Air Accidents Investigation Branch (AAIB). Table A1 in Appendix A presents the database of RPCs events (helicopters, tiltrotor and gyrocopters). As can be seen from this table, to date, most RPC events involve larger rotorcraft with conventional (non-digital) flight controls. Furthermore, many earlier recordings of RPCs were mostly associated with external underslung loads. This is true, as it is now well known that unfortunate combinations of helicopter and external load dynamics can introduce new lightly damped modes which are easily excitable by the pilot. If the pilot enters the loop, these oscillations amplify and a classical divergent RPC develops. The typical solution was to drop the load, which eliminated the problem.

For normal (internal load) operations, earlier recordings of RPCs were not really mentioned in the literature. Indeed, **RPCs have not typically been an issue for earlier helicopters** and not many were reported during operation. According to Ockier [ref. 16], three reasons may explain this.

The first main reason is that, until recently, there were no Fly-By-Wire (FBW) operational helicopters (with the exception of research vehicles). Figure 4 from ref. 16 presents typical equivalent time delays for some early FBW research helicopters.

Four configurations are presented in this figure:

ADOCS (Advanced Digital/Optical Control System) FBW system mounted on a specially modified UH-60 helicopter, named "Light Hawk" during an Army-sponsored programme in 1980's;
ARTI (Advanced Rotorcraft Technology Integration) demonstrator using an AH-64A Apache fitted with an advanced digital flight control system - This demonstrator helicopter first flew in October 1985 and was used to experiment with new technology that allowed '*hands-off*' flying. The idea was that using advanced flight control systems, the traditional cyclic, collective and foot pedal controls were removed and replaced with a four-way sidearm controller. Using this advanced FCS, the pilot could put the helicopter into, for example, a 60 degree bank or a 2g turn and maintain constant altitude and airspeed. With computers compensating for different torques, engine speeds etc., the pilot could concentrate outside the helicopter; he only needed to flex his hand on the sidearm controller for full manoeuvrability.
NASA-CH-47 system, a model-following control implemented for the first time on a tandem helicopter, the Sikorsky CH-47, in 1985 by NASA with the goal to improve different flying characteristics (increase task performance and simultaneously reduce pilot workload) on the helicopter on low-speed flight (later, such a system was also used in the RAH-66 Comanche of Sikorsky/Boeing for both low and high speed);
DLR's ATTHeS (Advanced Technologies Testing Helicopter System) in-flight simulator, a modified Bo105 helicopter equipped with a full authority non-redundant FBW control system for the main rotor and fly-by-light system for the tail rotor. In 1990's different programmes at DLR such as automatic hovering stabilization above a moving object or use of active side-stick during different tasks [ref. 18]

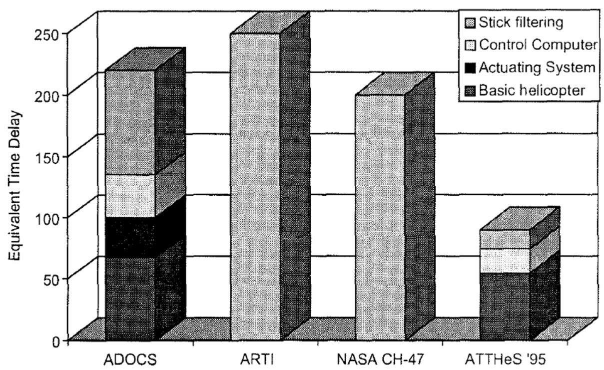

Figure 4 Typical equivalent time delays for fly-by-wire helicopters [from ref. 16]

Looking at Figure 4, one can see that many of these early FBW research helicopters did have high equivalent time delays (more than 200 ms, usually as the result of stick dynamics (input filtering), see also Table 1), and therefore were prone to RPCs. Indeed, for example in 1982, during the flight tests undertaken with the ADOCS system, rather severe PIOs were noted in high gain tasks such as slope landings [ref. 17].

The second reason for the absence of RPCs in earlier helicopters was that the typical APCs problems from fixed wing aircraft (e .g. fuselage bending, long control cables with bobweights, etc. [ref. 9]) were never an issue in helicopters.

The third reason probably has to do with the differences in piloting technique between helicopter and fixed wing (fighter) pilots. "*Highly unstable helicopters are the rule, rather than the exception and helicopter pilots are used to flying these unstable vehicles (the Bo 105 in hover, for instance, has an unstable Phugoid with a time to double amplitude of just over 2 seconds). Helicopter pilots are generally aware of the dangers of `getting into the loop' and tend to fly less aggressive than fixed wing (fighter) pilots. With the increase of controller sophistication in helicopters and the increase in simulator training, the helicopter pilots of the future may lose that gentle touch on the controls. When they do, PIOs may be just as frequent in helicopters as in fixed wing aircraft.*" [ref. 16]

Looking to Appendix A, one important conclusion appears, namely that, in modern helicopters, RPCs have become evident and can often be associated with couplings between the pilot and the lower flexible vehicle modes. Such was the case of V-22 tiltrotor full-scale demonstrator in 2003-2004 where a divergent PAO happened, caused by a pilot who coupled with the 2.3Hz asymmetric drive train torsion mode, primarily through the lateral stick to lateral cyclic gearing control path in the lateral axis. A secondary coupling responsible for this PAO appeared to be through the lateral cyclic to differential collective pitch control path, although this path had been treated previously in the 1986's full scale development V-22 with a notch filter due to drive system transient loads issues [ref. 19].

To better understand the incidence and the nature of RPCs, a brief statistical survey has been performed based on the incidents of Appendix A. Figure 5 shows the A/RPCs cases as a function of the PIO/PAO cases. Based on this figure it can be seen that there is still a major difference between A-and-RPCs: 77% of APCs are related to PIOs events, not involving elasticity whereas the RPC situation is much more entangled. At least 50% of reports, in fact, involve aero-servo-elastic phenomena (sections named PAO, PAO/PIO, Flexible modes, Slung-loads). Moreover, a deeper analysis of the reported cases, shows that also during a PIO, flexibility is inherently present, due to the interactions between rotor's rotating frame and fuselages fixed frame, and thus it is very hard to give a precise classification, as rigid and elastic phenomena are connected.

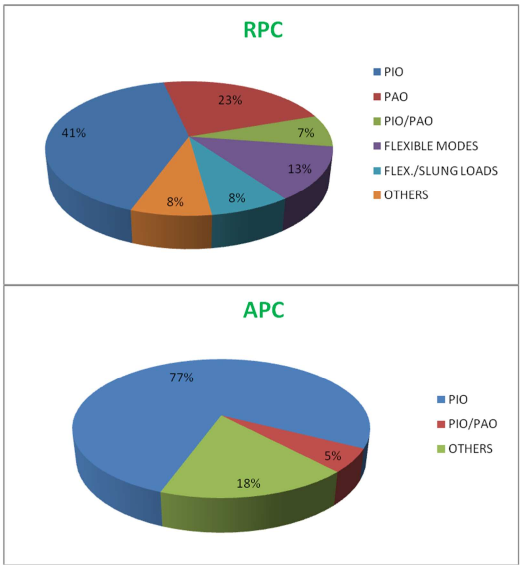

Figure 5 A/RPCs statistical analysis

As the level of automation is likely to increase and full-authority Fly-By-Wire are likely to be more common place in operational helicopters (at present operational on the NH-90, V-22 and BA609, but in the future probably also in commercial rotorcraft that hitherto have relied on manual control), it follows that more rather than fewer future RPCs are expected in the future. This situation appeared also in the 1990s for fixed-wing aircraft. McRuer [ref. 1, pp. 87], discussing the findings of the NRC Committee in 1995, mentioned that "*most new flight-by-wire commercial aircraft have experienced one or more events during development, some of them severe. The sophisticated flight test instrumentation fitted to development aircraft enabled those APCs to be identified and the problems eliminated before the aircraft was put into operation. Once in service, however, the aircraft FDRs (flight data recorder) and QARs (quick data recorder) cannot detect PIO problems, except in the most fortuitous circumstances. Therefore, investigations of commercial accidents seldom mention PIO as a contributory factor. Nevertheless, there may have been a few APC-related incidents in operational service. AIRBUS, which has more than 700 FBW aircraft in airline operation, has more FBW experience than any other manufacturer. In all the flight hours accumulated by this fleet to date, 10 possible PIO incidents have been identified. Although AIRBUS acknowledges only three as genuine PIOs, the problems associated with these 10 incidents have been identified and fixed.*"

APPROACH TO RPCS IN ARISTOTEL

The ARISTOTEL project's primary focus is Rotorcraft Pilot Couplings (RPCs) mainly because:

- Rotorcraft design tends to lag aircraft design by up to two decades, and their designers currently lack reliable criteria for specifically predicting RPC problems, and
- The particular characteristics and missions of rotorcraft may make them more prone to adverse couplings than fixed-wing aircraft.

The APC expertise of the project's fixed-wing partners (TsAGI and NLR) are being used to support the rotorcraft effort and to develop a general in-flight APC/RPC prediction method to be used in the early development phase of a new design.

Based on GARTEUR HC-AG16 experience [ref. 4], A/RPC phenomena have been divided into two groups based on the characteristic frequency range of such phenomena, i.e. low frequency and high frequency. In the high frequency range one can discuss about 'rigid body' RPCs – the realm of flight dynamics – and 'aeroelastic' RPCs – the realm of aeroservoelasticity (see Table 2). It is assumed that a certain overlap between these two RPC categories exists. As extension to the GARTEUR's approach, the frequency range considered for rigid body RPCs analysis has been raised from 1 Hz to 3.5Hz.The reason for this is that, especially for hingeless rotor configurations, *the body motion "speeds up" and the rotor dynamics enter into body dynamics*" [ref. 27]. Therefore, the rotorcraft flight mechanics low frequency dynamics and the 'active' pilot concentrating on performing his/her mission task in the closed loop are affected by the low frequency rotor modes (especially regressive flapping and regressive lagging).

Aeroelastic A/RPCs are oscillations in the bandwidth between 2Hz and 8Hz and correspond to higher helicopter frequency dynamics i.e. the inclusion of elastic airframe and main rotor blade modes. Usually for aeroelastic RPCs, a 'passive' pilot subjected to vibrations is considered. The passive pilot is usually modelled considering the pilot impedance in the form of a transfer function relating cabin movement to pilot input displacements. It is considered that an active pilot model for an aeroelastic RPC would require modelling of the pilot neuromuscular and cognitive system and this approach would not enhance the understanding of how vibrations affect pilot controls as they are too high in frequency to be adequately reacted to by a human.

For the frequency overlap range, the above mentioned classifications of A/RPCs correspond to a merger of the phenomena, with a mix of models and procedures for A/RPC detection. In the ARISTOTEL's approach as presented above, the main rotor blades modes are seen from 'rigid body' point of view in the non-rotating system and as 'aeroelastic' modes in the rotating system. It is thought that a parallel rigid body/aeroelastic approach may enhance the understanding of RPC phenomena in the critical range of 1-3.5 Hz, where many accidents have been observed [ref. 19].

Table 2: Characterisation of 'Rigid Body' and 'Aeroelastic' A/RPC

	Low frequency A/RPCs	**High frequency A/RPCs**	
		Rigid body aircraft	**Elastic body aircraft**
Frequencies	**Below 1.5 Hz** *APC frequencies are usually within 0.5-1.6 Hz (3-10 rad/sec).*	**Between 1.5-2 Hz (APC)** **Below 3.5 Hz (RPC)** *APCs frequencies usually exceed 2 Hz. Examples: Roll Ratchet, bob-weight.*	**Between 2-8 Hz**
Causes	1) Inadequate vehicle dynamic characteristics (aircraft + control system): • High order of the system, large phase delay, low damping, and others. • Control system delay. • Actuator or control surface rate limit. 2) High control sensitivity (command gain), low force-displacement gradient.	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 sensitivity, large pilot location relative to the centre of gravity)	1) Biodynamic interaction: The biodynamic interaction in the pilot-aircraft system arises due to aircraft structural elasticity and leads to involuntary manipulator deflections transferred to control system.
Characteristics	Pilot closes the loop according to the information received through visual or	The pilot closes the control loop due to **aircraft accelerations** acting on the body and the arm cause involuntary	The pilot closes the control loop due to **structural oscillations and inertial**

	acceleration perception channels.	manipulator deflections which go to the control system and lead to high-frequency A/RPC.	**forces** acting on the body and the arm cause involuntary manipulator deflections which go to the control system and provoke high-frequency A/RPC.
Critical components		Flight control system	Airframe modes
Pilot modeling	'Active' pilot concentrating on a task	'Active' pilot concentrating on a task	'Passive' pilot subjected to vibrations
Vehicle dynamics modeling	Flight mechanics	Flight mechanics	Structural dynamics

EXAMPLE OF A CLASSIC RPC PROBLEM

One "classical" adverse coupling characteristic observed in rotorcraft is the excitation of the low-damped main rotor regressive inplane mode by pilot's cyclic inputs which results in body roll and pitch aircraft vibrations affecting blade strength limits. This problem which is actually an air resonance of the inplane regressive/blade bending modes, was categorized in some references as PAO [ref. 19] and sometimes as PIO (as it does not involve biodynamic couplings, see ref. 4). The instability was observed for the first time in 1967 on the H-46D Sea Knight, the tandem rotor helicopter manufactured by Boeing-Vertol [ref. 19]. The instability existed at 3.2 Hz at airspeeds near the never exceed speed (VNE) and at low speed with high descent rates. It was created by the lightly damped main rotor regressive lag mode at 3.2 Hz, causing out-of-phase behaviour of the forward and aft rotors [ref. 28], coupling with the aft pylon's fuselage mode, a lateral bending/torsion mode. The instability was described by the pilots as a "shuffle" about the lateral, roll and yaw axes. After closer observation of the instability, it appeared that the AFCS system, introduced in CH-46D for flight path stabilization and the lag damping, was significantly affecting the behaviour of the 3.2Hz lag mode with airspeed. Lateral cyclic characteristics were also affecting the instability as the pilot's hand mass or effective grip force on the cyclic could create pilot feedback instability at 3.2 Hz. The critical results of the flight test program indicated that the source of the instability was insufficient lag damping in the rotor system with the significant initiation and/or sustaining mechanism being airframe structural flexibility, pilot lateral cyclic inputs and the yaw SAS. The results of the 3.2 Hz shuffle mode flight test program recommended the following changes to the CH-46D aircraft: a significant increase in blade lag damping and the implementation of a 3.2 Hz notch filter to suppress excitation of the mode. Due to the ongoing Vietnam War, none of these options were exercised and instead procedural mitigations were imposed recommending a reduction in airspeed, collective setting and/or manoeuvre severity to relieve the oscillation [ref. 19].

The same regressive inplane mode air resonance instability was reported also by ref. 29, this time at 1.8 Hz for the EC-135 helicopter. The air resonance mode of the EC-135 is described as a low-frequency mode characterizing the coupling between regressing lead-lag mode and body roll motion. Such a mode is characterizing especially the soft-inplane hingeless/bearingless rotor helicopters (Bo105, RAH-66 Comanche or EC-135) where the lead-lag motion is weakly damped. According to ref. 29, it appeared that, in the basic helicopter operation condition, air resonance was not an issue for the pilots operating the EC-135, the air resonance instability manifesting as a body roll oscillation which was existent but below the pilot perception level. However, when the helicopter was enhanced with an Attitude command/Attitude Hold (ACAH) control system for flying attitude command or flight path following tasks, it became apparent that, increasing too much the roll rate feedback gain, drove the air resonance mode unstable. This time the oscillation was perceived by the pilot as an oscillatory ringing in the helicopter roll response at a frequency of about 1.8Hz in the case of the EC-135. It was demonstrated that in this case the helicopter was PIO prone when applying the ADS-33 bandwidth criterion. The instability was eliminated by developing an air resonance controller which damped the coupled body-roll air resonance mode when rate feedback was used, independently from the main flight control system. Ref. 30 discussing the same air resonance problems concluded that "*Slow, stiff rotors would clearly be the most susceptible to the destabilizing effect of roll attitude to lateral cyclic feedback gain*".

Refs. 24 and 25 explained the physics of this mechanism of instability by defining so-called 'paths of energy' through which 'vicious' circles of energy transfer are formed between the flap-lag-roll degrees of freedom. It was demonstrated that, when using a controller, the roll motion pumps energy into the flap but there is no energy being pumped back from flap to roll (no instability problem). Especially in a soft-flapwise stiff-inplane rotor, the flap-lag motions pump energy into each other. Although the roll-lag motions are not directly related (the roll can pump energy into the lag but not the other way around), it is possible for the fuselage-lag mode to be driven unstable for a certain value of roll rate gain.

FOUR CATEGORIES OF A/RPCs

McRuer [ref.1] 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 have adopted this method since the classification. Figure 6 from ref. 31 presents the classification of these phenomena revealing the general three main A/RPCs categories according to McRuer [ref. 1]. This classification is also illustrative for the rotorcraft case.

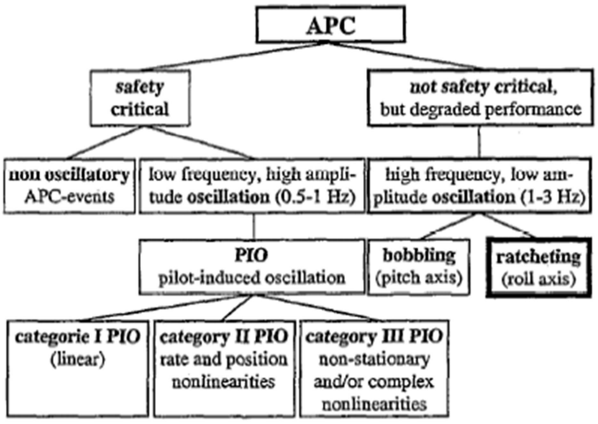

Figure 6 Classification of aircraft/pilot coupling phenomena (for fixed-wing aircraft) [ref. 31]

More recently, ref. 32 suggested the introduction of a 4th A/RPCs category for events that are caused by, or receive a major contribution from structural modes and their interactions with the pilot. These events, also referred to as PAOs, are of special interest for rotorcraft [ref. 19]. The four categories are explained below.

Category I A/RPC - Essentially linear PVS oscillations

A/RPCs in this category are essentially linear and are directly caused by excessive time delays or phase lags in the vehicle dynamics. These are typically a consequence of 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. These tasks require frequent small corrections from the pilot and thus increase the pilot's workload. Examples of high gain task are the slope landing for rotorcraft, and aerial refueling. Typical frequencies of Category I A/RPC are between 0.3Hz and 1.5Hz [ref. 1]. 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 during operational flying [refs. 1, 33, 34]. An example of an RPC in this category was induced during flight testing with Bolkov Bo-105 ATTHes helicopter (see refs. 21 and 16). 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 7. Looking at this figure, one should observe the typical signatures in the time histories of A/RPC events: 1) **oscillatory characteristics**; 2) the pilot roll inputs and the bank angle are **out-of-phase** 3) after the RPC is 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. 4) the **saw-tooth like deflections**, indicating control rate limiting.

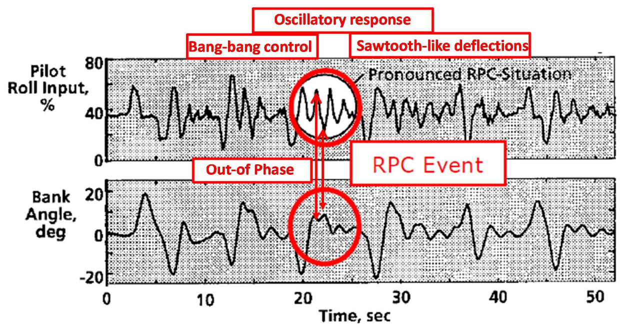

Figure 7 Bo105 ATTHeS roll attitude tracking tasks with 160ms added time delay (taken from [ref. 21])

To demonstrate that the time delay caused the RPC, ref. 16 plotted the time histories of the lateral position tracking task without and with a 100 ms added time delay (see Figure 8). 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 a combination of excess time delay and biodynamic coupling between the pilot's arm and the lateral accelerations of the rotorcraft. During A/RPCs events, pilots mentioned feeling "disconnected from the stick" or "suspecting" aircraft failures [ref. 10]. This confirms the suspicion that the proposed word in the definition relating to mental mismatch is key for triggering and sustaining A/RPC events.

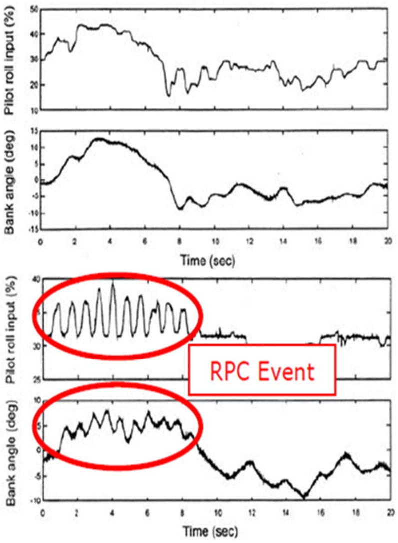

Figure 8 Bo105 ATTHeS lateral position tracking tasks without and with 100ms added time delay [ref. 16]

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 FCS or in actuator dynamics as shown in Figure 9 from ref. 35.

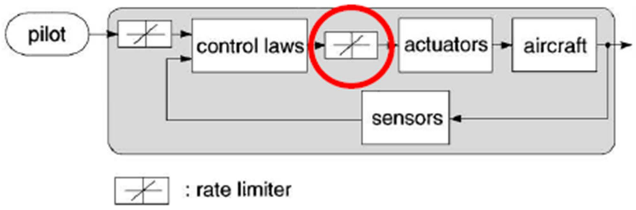

Figure 9 Typical locations of rate limiting elements (taken from [ref. 35])

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" behaviour is frequently used [refs. 1, 34]. After onset, the phase lag exhibits a jump. This is sometimes referred to as the "jump phenomenon" [refs. 35, 36]. This jump is clearly visible in the Bode and Nichols plots in Figure 10.

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

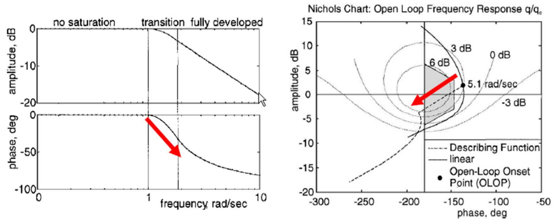

Figure 10: Left: Bode plot indicating phase jump after onset; Right: Nichols chart illustrating phase jump after onset (taken from [35])

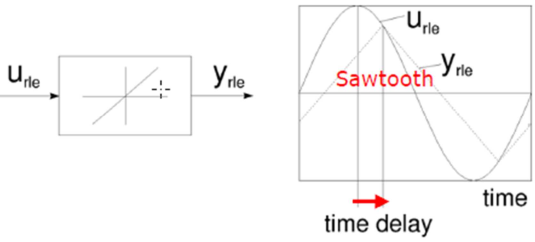

Figure 11: Time delay build-up due to rate limiting (taken from [ref. 9])

Although frequencies of the oscillation typically vary for each aircraft and RLEs, many ARC occurrences have a frequency of around 0.5Hz [refs. 1, 8, 47]. For rotorcraft, such RPC frequency is higher, around 1.8 - 3 Hz. The relatively new criteria for this category are based on, for example, the use of a describing function for the non-linear element [37, 38, 40] or the Open Loop Onset Point (OLOP) criterion [ref. 48]. The effects of rate limiting have either caused or sustained most APC events in the past, like in the YF-22 example [ref. 1].

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 [41, 42]. The same situation happened for the fixed wing F-8 DFBW (Digital Fly-By-Wire) test aircraft [ref. 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. 1]. Criteria specifically designed for this category are practically non-existent. The YF-22 APC case and the XV-15 and V-22 divergent lateral oscillations on the landing gear during ground taxi operations (first one predicted only on paper, the later encountered during flight test program) can be included in this category [ref. 19]

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 a “faster” type of A/RPC events with frequencies of at least 1Hz [ref. 8]. This category includes oscillations with a fully attentive or passive pilot in the loop, 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 also corresponds to the so-called “biodynamic couplings”, involving structural or aeroelastic modes of the aircraft [refs. 33, 34].

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 [refs. 1, 19]. Other examples for aircraft can be found in refs. [44, 45, 49]. In case of vibration feedthrough to the cockpit and biodynamical coupling, the pilot's limbs are shaken, causing passive and involuntary control inputs. A/RPC events of this kind are called Pilot-Assisted Oscillations (PAOs). Rotorcraft are especially prone to these types of RPCs, due to relatively high-amplitude vibratory environment. In ref. 19 an overview of these events regarding US Navy rotorcraft operations was presented. In ref. 45, a situation is presented where the dynamics of the pilot's arm and the collective handle is coupling with the rotorcraft vertical response. The example of the Bo105 RPC event that was shown in Figure 7 and Figure 8 belongs to this category.

In conclusion, there are many different kinds of A/RPCs. Thus, when discussing about an A/RPC event, there is not only one kind of A/RPC that can happen or not, on the contrary, a whole range of A/RPC types need to be considered, starting from minor but annoying A/RPCs to dangerous ones. “*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. 14]. Therefore, generally, A/RPCs can be considered safety-critical and non-safety critical to aircraft operations.

FUTURE ROTORCRAFT PILOT COUPLINGS

After an extensive investigation and review, the ARISTOTEL partners were able to identify some critical items for present and future trends in A/RPCs:

Newer design requirements

Stability vs. manoeuvrability Increasing the manoeuvrability requirements for the aircraft and rotorcraft could be observed in the mission requirements evolution of the civil and military customers. For example, new requirements of rotorcraft civil customers demand longer flight time periods over urban and mountainous regions. Because of possible obstacles and low flight profile missions (in case of law enforcement, passengers, medical transport and underslung load missions), an increase in helicopter manoeuvrability is recommended. This concern is especially relevant for missions performed providing Emergency Medical Services (EMS), where there is a requirement for the possibility to land on short fields with limited area and high obstacles. For military customers, good helicopter handling qualities for Nap-of-the Earth (NoE) missions are required in order to increase survivability on the battlefield. Also, attack reconnaissance helicopter operations require dynamic manoeuvring capabilities. An increase in helicopter’s manoeuvrability results in a decrease in its static stability margins and therefore a decrease in the available pilot reaction time. This too may affect the RPCs occurrence.

Flight Envelope Expansion Another trend observed for both aircraft and rotorcraft is the extension of flight envelope, i.e. increase of flying speed (also decrease of approach speed for fixed wing planes), altitude, ambient temperature and range. Several areas can be problematic for RPCs: 1) increase or maintain the never exceed speed VNE and flight altitude combined with the actual trend to decrease the main and tail rotor tip speed decrease (for environmental (greening) reasons) could cause additional RPC problems not met in earlier designs as the rotors are closer to the stall conditions 2) Improvements of capabilities for “Category A” rotorcraft such as reduction of necessary airfield size through specific control strategy closer to the vortex ring state can trigger future RPC problems.

Increase of AFCS autonomy There is a present tendency to increase the AFCS capabilities and include larger possible classes of manoeuvres performed with such systems. This is to develop towards the end goal of an optionally fully autonomous vehicle. Cooperation between the pilot with more sophisticated control system and vehicle equipped with these type of AFCS could be the source of possible A/RPC problems. Implementation of reliable pilot mathematical models combined with proper flight mechanics models should investigate in the future AFCS failure modes. This is especially true during emergency situations when pilot needs to react properly to hardware faults/unexpected flight situations [ref. 50]. Ref. 51 is a good example of the trade-offs that must be performed in rotorcraft FCS design.

Decrease of noise and vibration levels New rotorcraft, designed to meet 'green' requirements, could lead to more RPC problems. The future design of new aerial vehicles - such as heavy rotorcraft or large transport aircraft -relates to the development of more flexible conventional structures, or new structural design paradigms. The overall FCS must include the more pronounced flexibility effect 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. As a consequence, the lower frequency structural modes have a greater influence on the vehicle dynamic response. Additionally, weight reduction through the use of composite materials contributes to the development of more flexible structures. The structural flexibility also affects the vehicle aeroelastic stability where the pilot biodynamic feedback and FCS feedback can interact with vehicle structure, leading to pilot/control system assisted excitation of the structural modes.

Evolution of possible technical solutions

Advanced main and tail rotor schemes Designs for more controllable helicopters has resulted in stiffer main rotor hub structures. The rotor design evolution from fully articulated to hingeless and bearingless design results in an increase of the number of rotor modes affected by the pilot response. Implementation of new rotor control techniques such as Higher Harmonic Control HHC [ref. 52] or Individual Blade Control IBC [ref. 53] increase also the necessity for RPC analysis. Solutions, such as swashplateless rotors [ref. 53], may introduce new types of instabilities which can trigger RPCs. Tailrotor replacement by Fenestron, NOTAR or other solutions may also cause problems, and require RPC sensitivity analysis to discover specific critical operating conditions.

Increasing the role of electronics in cockpit design Commercial aircraft manufacturers are veering towards FBW control technologies. It is well known that high automation in the cabin reduces situational awareness [ref. 66]. While FBW can significantly enhance the aircraft manoeuvrability, it also increases controller bandwidth. This may result in adverse interactions between the human pilot-flight control system-aircraft dynamics. These interactions become more critical in the case of structural spill-over instabilities, due to poor control laws designs or incompatible airframe FCS updates. This highlights the need for robust control design techniques and effective analysis methods. Design of more autonomous AFCS with larger authority margin may lead to future RPCs. Design analysis should answer several questions such as: 1) is the pilot capable of maintaining control with partial/full AFCS out of order? 2) what is the pilot time delay for overruling the AFCS when needed and what are the appropriate parameters to be used for tuning the AFCS for safe operation 3) what are the most critical flight states when malfunctions of AFCS occur? Answering these questions requires appropriate pilot mathematical models and to complement extensive simulations with real human pilot participation.

Smart structures and smart materials incorporation into design New types of adaptable structures used on helicopter as well as additional controls could add new degrees of freedoms into RPC analyses

Evolution of certification requirements

Manoeuvrability requirements evolution There is a tendency to introduce new requirements in certification documents for performing specific manoeuvres. MIL-H-8501A and later MIL-F-83300 standards, which were applicable in the past, defined limits for helicopter responses based on pilot control input. ADS-33E [ref. 26] and, more recently, Handling Qualities of Rotorcraft with External Slung Loads [ref. 54], defined handling qualities per specific manoeuvres. Presently, very little requirements are given with respect to RPCs.

Civil design requirements evolution The evolution of civil helicopter design regulations - FAR 27/29, JAR 27/29, CS 27/29 for helicopters and FAR 23/25, JAR 27/29, CS 27/29 shows that the stability requirements have strengthened in time (such as damping requirements, pilot response delay time with AFCS). Fulfilling both the stability specs for civilian market and manoeuvrability specs for military requires the use of trade-offs. Future RPC analyses could help to find optimal control strategy for the physical pilot capabilities.

Environmental requirements evolution The 'green' environmental aspects, such as restrictive noise, vibration, pollution requirements, new structures, materials, systems, control strategies etc., which are presently not included in the design but might become compulsory in the future could affect the RPC level. The ACARE agenda of the European Community [ref. 55] together with the JTI “Clean Sky” initiatives (http://www.cleansky.eu/) for implementation of new technology, smart structures, new materials, new control strategies for take-off and approach flight paths in both fixed wing and rotorcraft (increased manoeuvrability, higher climb and descend ratios near airfields and helipads) may affect the tendencies for RPCs.

CONCLUSIONS

This paper presents a review of the current status on RPC problem and how it was tackled in the ARISTOTEL project. This European Community project, started in Oct. 2010 and running into 2013, intends to give design and simulator guidelines for investigating rigid-body and aeroelastic A/RPCs of future aircraft and rotorcraft. The present paper presented a new extended database of RPC events and proposed a new definition for these phenomena. An extensive discussion on future RPCs shows that, modern designs are more RPC prone than their predecessors and, therefore designers should be acquaint with specific knowledge for understanding these problems.

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Appendix A

Table A1 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. 19]
H	1967	-	CH-46D	Flexible mode air resonance "Shuffle Mode"		[ref. 19]
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. 19]
H	1968	-	CH-47	Rotor/Sling load bounce		[ref. 19]
H	1970	-	AH-56	Flexible Control Actuation system		[ref. 60]
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. 61, 64]
H	1978	-	CH-53 E (USN)	Flexible Modes/Sling Loads		[ref. 61]
H	1980	-	CH-53 G (GAF)	Flexible Modes/Sling Loads	PAO	[ref. 62]
H	1980	-	CH-46E	Flexible mode-air resonance "Shuffle Mode"		[ref. 19]
H	1981	-	SH-60	Flexible mode ground resonance		[ref. 19]
H	1988	-	UH-60 ADOCS	Excessive Time Delays		[ref. 63]
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. 59]
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. 19]

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. 19]
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. 19]
H	1992	-	S-76B	Flight control mode shifting	PIO	[ref.19]
H	1993	-	BO 105 ATTHeS	Time delay/Attitude Command		[ref. 65]
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. 21, 16]
T	1997		V-22B Osprey [EMD]	1.4 Hz High Focal Roll mode oscillation due to change in mass balance weight; relaxation of pilot grip on cyclic	PAO	[ref. 19]
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. 14]
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 bounce leads 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*