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Practices to identify and preclude adverse Aircraft-and-Rotorcraft-Pilot Couplings – A design perspective ☆

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ABSTRACT

Understanding, predicting and supressing the inadvertent aircraft oscillations caused by Aircraft/Rotorcraft Pilot Couplings (A/RPC) is a challenging problem for designers. These are potential instabilities that arise from the effort of controlling aircraft with high response actuation systems. The present paper reviews, updates and discusses desirable practices to be used during the design process for unmasking A/RPC phenomena. These practices are stemming from the European Commission project ARISTOTEL *Aircraft and Rotorcraft Pilot Couplings – Tools and Techniques for Alleviation and Detection* (2010–2013) and are mainly related to aerodynamic and structural modelling of the aircraft/rotorcraft, pilot modelling and A/RPC prediction criteria. The paper proposes new methodologies for precluding adverse A/RPCs events taking into account the aeroelasticity of the structure and pilot biodynamic interaction. It is demonstrated that high-frequency accelerations due to structural elasticity cause negative effects on pilot control, since they lead to involuntary body and limb-manipulator system displacements and interfere with pilot's deliberate control activity (biodynamic interaction) and, finally, worsen handling quality ratings.

Contents

Abbreviations: AFCS, automatic flight control system; A/RPCs, Aircraft-and-Rotorcraft-Pilot Couplings; BA/BT/BAT, boundary avoidance/boundary tracking/boundary avoidance tracking; BDI/BDFT, biodynamic interaction/biodynamic feedthrough; DOF, degree of freedom; FBW, fly-by-wire; FCS, flight control system; HQs, handling qualities; LTI, linear time invariant; MTE, mission task element; OLOP, open loop onset point; PAC, phase aggression criterion; PRE–PAC, prediction algorithm–phase aggression criterion; PIO/PAO, pilot induced oscillations/pilot assisted oscillations; PIOR, PIO rating; PVS, pilot-vehicle system; RLEs/PLEs, rate limiting element/position limiting element; ROVER, real-time oscillation verifier; RMS, root mean square; RSA, robust stability analysis; SAS/SCAS, stability augmentation system/stability and control augmentation system; TCL, thrust control lever

☆ "Beware, it's too easy to make a mistake and let an impressive printout or graphic output lead you to assume the results are correct, but they may not be." (Troy Gaffey, Bell Helicopter)

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1. Introduction

Adverse Aircraft/Rotorcraft-Pilot Coupling (A/RPC) have challenged designers since the first manned flight of the Wright Brothers over a century ago [81,82]. A/RPCs are unwanted phenomena originating from an anomalous/undesirable discord between the pilot's intentions and the aircraft's response. Such phenomena have always been a potential flight safety-critical issue for both fixed and rotary wing aircraft. They may result in annoying aircraft oscillatory/non-oscillatory instabilities which degrade the vehicle's flying qualities, increase the structural strength requirements and sometimes even result in catastrophic accidents. Until 1995, A/RPC events were perhaps still better known as pilot induced oscillations (PIO) and pilot assisted oscillations (PAO). PIO[1] implies that the pilot inadvertently excites divergent vehicle oscillations by applying control inputs that are in the wrong direction or have phase lag. PAO[2] is the result of involuntary control inputs of the pilot in the loop that may destabilise the aircraft due to inadvertent man–machine couplings. Today it is agreed that the cause of a particular undesirable A/RPC is not necessarily nor entirely due to the pilot but it is often ultimately associated with some anomalous aircraft design features. Throughout this paper, the term "A/RPC" will therefore be used.

> "*Almost like clockwork PIO becomes an important problem to solve every 10 to 15 years, usually in association with at least one highly visible event*." [177].

As first examples, the Wright Brothers' first flights [81,82] were very challenging to fly because the aircraft was marginally stable and needed ample pitch control power. As a result, overcontrol in the pitch attitude and stick-force reversal could occur. Especially in gusty conditions, it is reported that Wilbur and Orville Wright were continuously correcting their control input to keep a steady flight path. Accidents occurred so frequently that, in the Wright Brothers l908 aircraft, the "Flyer", 80% of the licensed pilots were killed. Subsequently the "Flyer" was modified to use trailing edge ailerons to reduce adverse yaw, and the canard was replaced with an aft tail to improve stability and stall control. Many of the APCs recorded in older aircraft (1950s and earlier vintage) were due to poor stability characteristics (low inherent damping of the short period or Dutch roll aircraft modes). For rotorcraft, the first recorded RPC occurrence concerned the experimental Firestone XR-9 helicopter in 1945 [83,85]. The novel feature of the XR-9 was a floating (gimbal) rotorhead design where the rotor hub and blades were able to pivot in a gimbal motion about the gimballed joint connecting the rotor to the helicopter. It was this feature that caused inadequate helicopter control and pilot difficulties. This made XR-9 "*not satisfactory for use by relatively inexperienced and untrained pilots because of its unstable characteristics*" [83].

The first major push to comprehend and eliminate APC came in the early 1960s. At that time at least three major APC incidents occurred on four different aircraft: (1) the Bell X-2 Starbuster high speed research aircraft; (2) the X-15 rocket-powered aircraft; (3) the Northrop T-38A supersonic jet trainer, and (4) the McDonnell F-4A Phantom II "Sageburner" supersonic all-weather fighter known to have broken many altitude and speed records during the period 1959–1969. The research of that time is best encapsulated in reference [52]. The Bell X-2 APC incident occurred in the 1956 [83] and is a classic example of the human limitations in controlling a vehicle with poor handling qualities. The cause of the accident was an excessive/adverse roll-pitch–yaw coupling. The pilot initiated a left turn at a too high Mach number ($M=2.8$) in an attempt to set a new speed record. As the turn progressed, the angle of attack (AOA) increased and aileron deflection was applied to limit the increasing bank to the left. The adverse yawing moment due to aileron deflection exceeded the available directional restoring moment due to sideslip. Yaw/roll coupling motions increased in intensity until the critical roll velocity for inertial coupling was exceeded. Violent, uncontrollable motions occurred about all axes approximately 17 s. High positive and negative accelerations were imposed on the aircraft, which finally entered an inverted spin. For a more detailed explanation of the incident the reader is referred to Ref. [84]. The X-15 APC incident occurred on January 25, 1959 during its first gliding flight approach and landing. Analysis of the event indicated that the FCS flown with the pitch-damping system off combined with a high precision landing task led to the APC. The T-38A APC occurred on January 26, 1960 during a demonstration flight and it was "*as severe as one can get without an actual breakup of the aircraft*" [1,50] (vertical acceleration oscillations that peaked at −10 g and +8 g). The event took place at high subsonic speed (Mach number 0.91) and involved an initial instability due to the coupling between the flight control system (FCS) and the aircraft which was further aggravated by the pilot who disengaged the FCS. The F-4 Sageburner destructive APC occurred on May 18, 1961 during an attempt to set a high-speed, low-altitude record. During the attempt a pitch damper failure led to the severe APC that resulted in a catastrophe.

The second important period of high profile A/RPC events

[1] In the past many other terms were used to designate PIO events, e.g. "pilot in the loop oscillations", "pilot involved oscillations" and "pilot augmented oscillations". The term "pilot induced oscillation" is retained within this report due to its widespread acceptance.

[2] PAO were designated in the past as "pilot out of the loop oscillations", "pilot activated oscillations", "aeroelastic PIO" or "high frequency PIO". The term "pilot assisted oscillations" is retained within this report due to its widespread acceptance.

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