1. Publishable summary

Project acronym: ARISTOTEL

Project full title: Aircraft and Rotorcraft Pilot Couplings – Tools and Techniques for Alleviation and Detection

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Project context and objectives

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 all aerospace community. In October 2010 the European Commission launched, under the umbrella of the 7th Framework Programme (FP7), the project ARISTOTEL - Aircraft and Rotorcraft Pilot Couplings – Tools and Techniques for Alleviation and Detection. With a duration of 3 years (2010-2013) and 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, ARISTOTEL aims at advancing the state-of-the-art in predicting the A/RPC susceptibility for modern aircraft/rotorcraft. In this sense, the project aimed at contributing to the European Union's initiative to reduce aviation accidents by 80% by 2020.

The understanding of the occasional and yet dramatic appearances of A/RPCs has driven significant past research, which continues in the present and will no doubt present challenges for the future. A/RPCs can be extraordinary and memorable events involving unique, fascinating and often apparently unpredictable complex dynamic interactions between the pilot and the air vehicle. Adverse A/RPCs have been always a critical issue for flight safety for both fixed and rotary wing aircrafts. They have manifested themselves since the early days of manned flight - the earliest recorded examples of such phenomena in powered aircraft date back to the Wright Brothers 1902 aircraft.

However, for modern aircraft, it has become increasingly clear that the rapid advances in the field of high response actuation and high augmented flight control systems (FCS) have increased the sensitivity to the appearance of complex oscillations related to unfavourable Aircraft-Pilot Coupling (APC) and Rotorcraft-Pilot Coupling (RPC), respectively. “*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*” (McRuer, 1995) 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. The philosophy of the development of the fly-by-wire system on rotorcraft is rather different from that implemented for aeroplanes. More precisely, for airplane, the main goal of the fly-by-wire system is to increase the performances of the aircraft in terms of controllability and manoeuvrability. Improvement in these performances generally results in a decrease in the dynamic stability of the aeroplane and this is, then, artificially compensated by the fly-by-wire system. As rotorcraft are unstable by nature and highly coupled between axes, the approach followed in designing a fly-by-wire system is radically different and consists, at a first stage, of restoring acceptable handling qualities for the vehicle and, at a second stage, in reducing the pilot's workload.

It was therefore the main goal of the present project to design the tools and methods capable to prevent and detect A/RPCs early in their onset, and hence to reduce the rate of accidents caused by unpredictable A/RPC events.

Work performed since the beginning of the project and the main results achieved so far

In order to achieve ARISTOTEL’s goals, the consortium decided to understand the effects of each factor in the pilot-vehicle system (PVS) closed loop for a modern rotorcraft (this is true also for an aircraft), see Figure 1. The input into the system is the Task. This can be anything from a tracking task, manoeuvre or forcing on the stick. The Pilot uses the task to give inputs to the stick in order to control the integrated rotorcraft system. He/She is of course the essential element in the PVS as he/she is the one ultimately handling the circumstances. In modern rotorcraft the stick is connected to the vehicle not directly but through an integrated control system which comprises Inceptors (the physical device the pilot applies force to, e.g. a wheel, a side or a centre stick, or 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, digital filters of a Flight Control System etc., and Display laws. This control system is used by the pilot to control the inherent Rotorcraft dynamics. The output of the rotorcraft system is fed back to the pilot and the control system. The pilot or the AFCS gives adjusting control inputs based on the needed states to fulfil the task. While presently most of the inceptors used in rotorcraft are passive – i.e. the only feedback the pilot receives is the fixed tactile information (stiffness, damping and inertia) from the springbox of the conduit in which the pilot inputs are connected – future configurations will benefit from active inceptors. Such inceptors will give variable tactile information to the pilot in real time depending on the flight condition. This variable information is obtained through the fly-by-wire system which is programmed in such a way to dictate the level of resistance the pilot will feel at any given stick displacement. In this way “soft stops” in the stick can be added to the tactile cues of the pilot in order to inform the pilot that he/she has reached the operational or design limits of the airframe, gearbox, or engine, and thus increase safety.

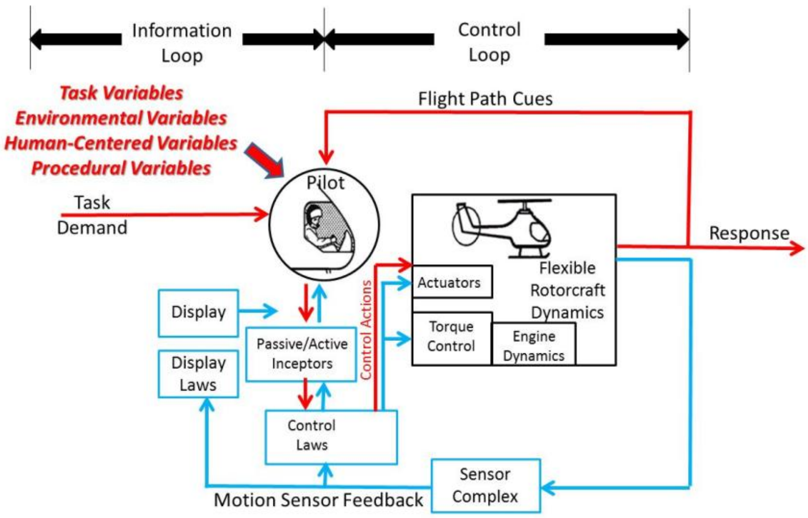

Figure 1 Pilot in the loop system in a modern rotorcraft

From this understanding of the pilot in the loop, ARISTOTELians developed tools capable of preventing and detecting A/RPC onset. We considered that the most functional classification of A/RPCs is based on the frequency content of the dynamics involved. In this sense, a distinction has been made between Rigid Body A/RPCs (frequency range 0-2 Hz) and Aeroelastic A/RPCs (frequency range 2-8 Hz). In the first class of phenomena, sometimes known as Pilot Induced Oscillations (PIOs), the pilot response is dominated by a behavioural process (a mental mismatch, as stated above), whereas in the latter, known as Pilot Assisted Oscillation (PAO), the pilot becomes an involuntary link between the seat motion and the controls, thus acting like a mechanical impedance. In contrast to the fixed-wing world, where most present APC events are characterized as PIOs, the available records clearly show that PAOs contribute to a significant proportion of RPC-related rotorcraft accidents. A recent database of incidents indicates that 77% of APC can be related to PIO events, whereas in the case of RPC, at least 50% involve aero-servo-elastic phenomena. For the frequency range involved in rotorcraft PAOs, the pilot’s unintentional control input actions couple with, for example, rotor blade dynamics, airframe flexibility and servos, amongst others, thus requiring more complex tools for effective computational simulations. Moreover, due to their low frequency nature, some aeroelastic phenomena may play a non-negligible role in helicopters PIOs.

We realised for example that there is a need for a better understanding of pilot behaviour in a critical condition such as A/RPC. Classically, there are two general formats of pilot behaviour: synchronous and compensatory. Synchronous control is the simplest possible form of pilot behaviour in which the pilot, exposed to oscillatory inputs, will adapt his inputs with no special compensation or phase lag w.r.t. the aircraft. It is said that only “input” information is available to the pilot. Synchronous pilot behaviour results in high level of control where the highly-skilled pilot has extensive knowledge on the vehicle dynamics to the point where he/she no longer relies on feedback signals. Compensatory control means that the pilot will adopt a feedback scheme, compensating continuously the perceived errors or aircraft motions. It is said that only error information is used by the pilot to generate control steering inputs in the vehicle system. In reality, of course, both error and input information is used by the pilot to command the aircraft/rotorcraft, which corresponds to a “pursuit” behaviour. Up to date, the majority of work in pilot manual control has dealt with compensatory control modelling. In the critical condition of A/RPC, it seems that pilots are controlling the aircraft based on a succession of “opposing events” wherein they continuously attempt to survive by alternatively attempting to track the opposing risks describing those events. In other words, in an A/RPC, rather than using compensatory control to restraint the situation, the pilots are tracking a hazard, expressible as a boundary in the so-called concept of Boundary Avoidance Tracking (BAT). Our project developed BAT models for pilot behaviour in an A/RPC that will revolutionize the understanding of pilot behaviour in an A/RPC.

Another interesting development of ARISTOTEL related to biodynamic couplings (BDC). BDC is related to the pilot involuntary inputs given due to aircraft oscillations felt in his seat. To understand which particular helicopter vibrations induce adverse biodynamic couplings (BDC) effects and which mission tasks are more prone to such effects, for both helicopters and fixed wing aircraft, biodynamic simulator test trials were performed in the project. For helicopters, the results revealed some important conclusions, for example: BDC depends on the control tasks: for the different control tasks (i.e., different neuromuscular settings), a different level of BDC was measured; BDC depends also on the control (disturbance) axis: the highest level of BDC is measured in sway direction, followed by the surge direction. The project assessed the effect of structural elasticity on aircraft handling qualities. This approach allowed splitting pilot activity into ‘active’ component (active pilot’) and ‘passive’ component (‘biodynamical pilot). The splitting was based on a handling qualities pilot rating increment due to high-frequency oscillations. The experiments for fixed wing aircraft demonstrated that varying the manipulator characteristics, i.e. using either a control yoke (wheel) system like in most of the airliners, a central stick like in most military aircraft or a side-stick as in the new fly-by-wire airliners, affected also the BDC. The greatest worsening due to biodynamic interaction between the pilot and the elastic accelerations corresponds to the central stick system. This demonstrates that in many modern civil aircraft (such as Airbus A320, Airbus A380 using a side stick manipulator) and military aircraft (such as Daussault Rafale, F-22 Raptor, F-35 Joint Strike Fighter with a side-stick and Eurofighter Typhoon and Mirage III with a centre-stick) BDC effects are more important than in the past. Also, helicopters and tilt rotors (as V-22 Osprey) use mainly centre-stick manipulators and thus are BDC sensitive.

The ARISTOTEL project considered that piloted simulation trials are an essential tool in understanding and improving the state-of-the-art in A/RPC. Four motion-based generic simulators (i.e. SIMONA at Delft University & HELIFLIGHT-R at Liverpool University for Rotorcraft Research, FS-102 simulator at TsAGI and GRACE at NLR for fixed wing research) were involved in the project, see Figure 2. Different test campaigns (rigid body testing, aeroelastic testing, biodynamic testing) were conducted to assess the A/RPC predictions (see Figure 2). Using these simulators, a whole database of tasks has been developed to unmask A/RPCs early in the design.

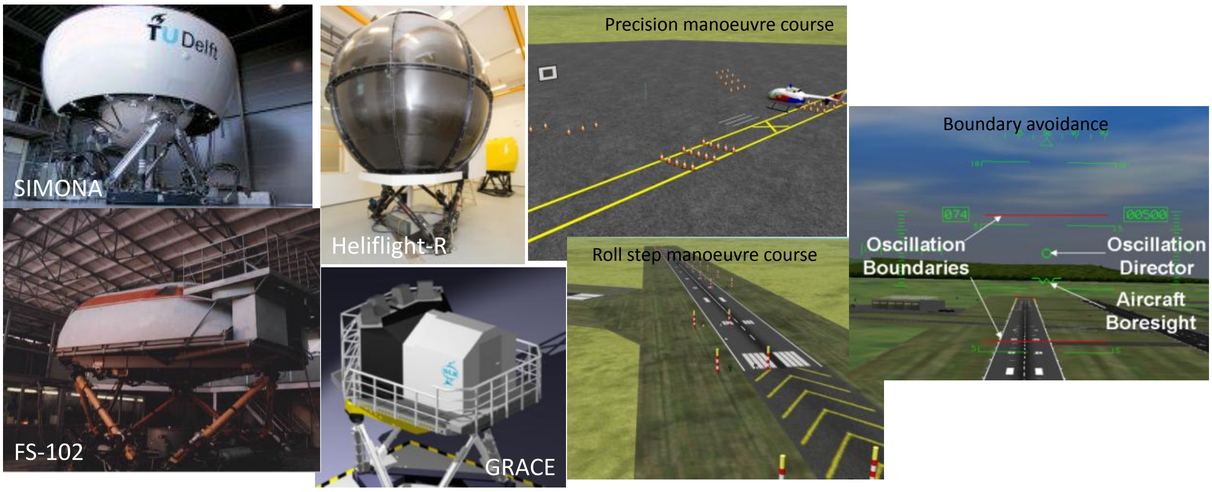

Figure 2 Simulators used in ARISTOTEL and tasks developed to unmask A/RPCs

Expected final results and their potential impact and use

The ARISTOTEL project proved that the incidence of A/RPC events could be reduced through more effective and consistent use of tools and capabilities during modelling, analysis, design and testing. End products of the project are:

1) A revolutionary way to look at pilot decisions and control during an A/RPC;
2) New A/RPC design guidelines and criteria for the industry to unmask A/RPCs during design;
3) Protocols and guidelines on how to test for A/RPC in the simulator.

We tried in this project to understand 'exotic' couplings that are responsible for A/RPCs and learned more about the complexity of the pilot and how this relates to vehicle dynamics. We acquired more knowledge on how to test for A/RPC. On this basis, we proposed new approaches to address the A/RPC risk. In this sense, we contributed to the:

1) Minimization of the factors that lead the pilot to lose the aircraft control
2) Enhancement of European and international aircraft/rotorcraft safety and
3) Strengthening of the European Aeronautics Industry competitiveness for time- and cost-effective design tools.

As lasting impact of this project we foresee that the tools that we have developed for A/RPC analysis will be used for designing future generation aircraft. At the moment the aircraft community is discussing breakthroughs in many aeronautic fields such as active controls, new airfoil concepts, flow control, new composite materials, fly-by-wire technology and new propulsion systems. Revolutionary changes in the design are possible when the "rules" are changed, in other words when new requirements are introduced. Safety is one requirement for future aircraft design and multi-disciplinary design will be capable of dealing with A/RPCs much earlier than it is currently the case It will be our future task to integrate our new tools and findings related to A/RPCs into the current design-team efforts to address A/RPC. We learned in this project how complicated A/RPCs can be with regard to their understanding and detection, especially during operational flight, and made also progress in detecting them.

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