# Nitros

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# NITROS An Innovative Training Program to Enhance Rotorcraft Safety

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## ABSTRACT

Helicopters are currently used in important applications providing a valuable contribution to society and economic growth. Thanks to the operational flexibility of helicopters it is possible to accomplish complex missions. If the expansion of the usage of rotorcraft is to follow the pace of growth achieved by the fixed-wing public transport in the last years, several issues need to be urgently addressed to increase the use and the public acceptance of rotorcraft. Aspects related to complexity of the operations and safety are of primary importance, due to the fact that in the last 20 years helicopter accident rates, worldwide, remained unacceptably high, when compared to fixed-wing aircraft. The complexity of the phenomena involved in rotorcraft flight calls for the training of engineers with a genuine multidisciplinary background. This paper presents the doctoral research and training program set up under the Marie Skłodowska-Curie Action of the European Union to address complex solutions to rotorcraft safety.

## INTRODUCTION

Helicopter accident and fatal helicopter accident rates have a clear decreasing trend, as shown in the report of the International Helicopter Safety Team (IHST) presented at HAI Heli-Expo this year[1] (Ref. 1). However, the current rate is still too high. Unfortunately, it is very difficult to retrieve data on accident per flight hours that is the typical safety rate used in aviation, because it is still problematic to collect flight hours for the global helicopter fleet (Ref. 2). The current rate for commercial airplane is of about 22 non-fatal (and 4 fatal) accidents per 10 Million movements (source[2] Ref. 3), and given the fact that the average flight time is close to 2 hours, this corresponds to about 11 accidents per 10 million flights. In 2000 Harris et al (Ref. 4) estimated that it is ten times more likely to be involved in an accident if flying in a helicopter than in turbojet fixed-wing aircraft. However, in 2004 Fox (Ref. 2) estimated an accident rate for Bell helicopters of 3.9 per 100,000 hours. So, it is reasonable to say that even today the rate of accident per flight hours of rotorcraft is between one and two orders of magnitude higher that for commercial airplanes.

The concern about helicopter accidents is so high that in 2005 the IHST was formed to address the factors leading to the unacceptable high rate in helicopter accidents. Since then IHST has achieved substantial reductions -- 18.6% for accidents between 2006-2011 and 32% between 2013-2017 -- concentrating on training, pilots' awareness and operators through the dissemination of very effective key recommended best practices (Ref. 1). However, we are still short with respect to the target of an 80% reduction in the accident rate that was sought in the 10-years goal set by IHST in 2005.

Given the strategic role played by rotorcraft in many critical community services, flight hours are expected to grow in the future. The Federal Aviation Administration (FAA) in its 20-year Annual Forecast anticipated a grow rate of 2.2% per year for rotorcraft hours flown[3] . Additionally, the future of rotorcraft is linked to new designs for *on-demand* and personal aviation, based strongly on multi-rotor Vertical Take-Off and Landing (VTOL) air vehicles for urban mobility (Ref. 5). At present, several key research programs, some of them financed by the European Union (EU), are exploring innovative VTOL that may start the transport

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[1] Retrieved at http://www.ihst.org/Portals/54/IHST Worldwide Partners2018.pdf April 2018

[2] Retrieved at https://www.easa.europa.eu/document-library/general-publications/annual-safety-review-2017 April 2018

[3] Retrieved on March 2018 at https://www.faa.gov/data_research/aviation/aerospace_forecasts/

revolution long-sought by the pioneers of vertical flight and foreseen by ACARE's vision 2050 (Ref. 6).

It follows that in the future rotorcraft safety will be under even more scrutiny by regulatory authorities and rotorcraft operators. To reach a more extensive use of rotorcraft in our communities a great leap forward in safety must be achieved, better taking into account the risks associated with operations.

A recent research activity launched in 2016 under the umbrella of the Marie Sklodowska Curie Joint Doctorates Programme in European Union – Network for Innovative Training on ROtorcraft Safety (NITROS) project[4] – aims to train, up to doctoral level, a new generation of talented young engineers to become future specialists in developing innovative approaches to address rotorcraft safety issues. NITROS researchers will learn that rotorcraft safety requires, at the engineering stage, the highest level of interdisciplinary cooperation. The following sections will present the goals of this network and the strategies put in place to enhance safety awareness in the future generation of people that will work on rotorcraft design.

## STATUS OF ROTORCRAFT SAFETY

The safety of rotorcraft is clearly related tounique missions they are asked to perform. Airliners operate from airport to airport, so most of the time they are far from obstacles, while rotorcraft are employed in many complex operations: offshore operations, search and rescue, coastguard, firefighting, disaster relief, territorial control, monitoring and inspection, heavy-lift support to construction and other sectors, aerial filming and media support, and this makes a huge difference in the realistic safety targets that can be achieved given the significant time spent close to terrain and obstacles and in harsh environments. Additionally, rotorcraft have naturally (i.e. without any artificial stability augmentation) limited stability; they have significant cross-couplings of control making, for some types, potentially difficult for the pilot to operate without losing control in harsh environmental conditions; when the visual conditions degrade and the pilot has difficulty seeing the terrain and horizon references, there is a high risk of spatial disorientation, with consequent departure from the desired flight trajectory. So, it seems very important to consider safety not as simply related to airworthiness of the design but linked also to operational risk.

**Figure 1. Key pillars of flight safety**

The risk is a measurement of the chances of a hazard. In fact, it is the combination of the predicted severity – i.e. criticality – and likelihood – i.e. probability – of the potential effect of a hazard. Safety is the management of risk associated with any operation, so it is the union of all action taken to bring the risk to an acceptable level. The risk associated with a flight is tightly related to operations and should be considered a function of many parameters related to the environment and where the operation takes place.

In the '50s and the '60s the US Air Force Ballistic Missile Division introduced the concept of "System safety", where one of the key aspects was that everything contributes to the response of the "system" and so all failures – of parts of the aircraft but also of the human operators, the management system, and the environment – affect the final outcome of the system (Ref. 2). In the helicopter world most of the times the system has been considered the entire aircraft (Ref. 2). However, to manage risk properly, and so increase safety, it is important to take into account the other elements that contribute to the system and consequently develop an approach to safety that is linked to operational risk. This approach is proposed by Leonardo Helicopter Division in Ref. 7, where the idea is to develop operation standards for helicopters that are strictly related to operation risk. This means that the higher is the risk of the specific operation to be performed the more stringent should be the design requirements. Hence the designer must be able to identify clearly the risk associated with any design choice in relation to the different operative scenarios. Additionally, it will allow to erase the myths such as "Twin-engine helicopters are always safer than single engine helicopters. The rest of the aircraft other than the engines are the same on single or twin-engine helicopters, so it can be disregarded" (Ref. 2), that tend to ignore that risk is intimately associated with the type of mission, and that in specific situations with the appropriate safety assessment a flight on a single engine rotorcraft could be safer.

Disproving such a myth in aviation was perfectly exemplified by the development of the ETOPS (Extended-range Twin-engine Operational Performance Standards), introduced in 1985 to apply an overall level of operational

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[4] http://www.nitros-ejd.org

safety for twin-engined airplanes which was consistent with that of the three and four-engined airplanes the only ones allowed to fly transoceanic routes at that time, to which no restrictions were applied (Ref. 8). In reality, this introduction “improved the safety of commercial aviation: no ETOPS flight has been lost because of a danger that ETOPS was meant to address” (Ref. 8). So, definitely a fresher look on how to deal with safety issues could be what is needed in a consolidated sector such as rotorcraft.

Part failure represents a very small fraction of accidents, so airworthiness problems contributes little to the causes that must be primarily sought in the interaction of the vehicle with the other element of the system (Ref. 2,3). In an analysis of accident statistics between 1995-2010 performed in Ref. 10, only 5% of accidents belong to airworthiness failures, while 40% are related to pilot awareness, skills and judgement, 10% are related also to the risk associated with environmental conditions and another 5% to mission risk associated with hostile areas of operations. In fact, borrowing Padfield’s (Ref. 9) description of the key factor that influence a mission, it is possible to state that the safety of a mission performed by a helicopter derives from analysis of the interactions amongst three key pillars – the vehicle, the pilot and the operational environment (see Figure 1). A significant number of accidents are the result of the unforeseen interactions between those elements. The training approach chosen in NITROS is founded on those three pillars.

#1 SIMULATION AND PREVENTION OF ICE FORMATION AND SHEDDING ON ROTORCRAFT

#2 IN SERVICE HEALTH MONITORING FOR ROTORCRAFT STRUCTURES

#3 INNOVATIVE DESIGN FOR TILTROTOR COCKPIT FOR THE REDUCTION OF PILOT WORKLOAD

#4 ROBUST FLIGHT CONTROL OF ROTORCRAFT MANOEUVRES IMMERSED IN OBSTACLE’S TURBULENCE

#5 ROTORCRAFT WAKE MODELLING

#6 DEVELOPMENT OF THE PHASE AGGRESSION CRITERION FOR ADVERSE ROTORCRAFT PILOT COUPLING PREDICTION AND REAL-TIME DETECTION

#7 MITIGATION OF AIRWAKE HAZARDS

#8 MODELLING OF BROWN/WHITE-OUT

#9 ENHANCED HELICOPTER HANDLING QUALITIES THROUGH VIBRATORY LOADS EXPLORATION

#10 REVEALING ADVERSE ROTORCRAFT PILOT COUPLINGS INDUCED BY FLIGHT CONTROL SYSTEMS

#11 UNDERSTANDING THE USE OF AUTOMATION IN HELICOPTERS

#12 ALLEVIATING FLIGHT SIMULATOR NEGATIVE TRANSFERENCE FOR HELICOPTER OPERATIONS

**Figure 2. The twelve research projects of NITROS**

## THE MSCA PROJECT FOR RESEARCH AND TRAINING

Exploiting the analysis undertaken by the European branch of the IHST (Ref. 10), three main threats to rotorcraft safety have been identified. This analysis led to the following three NITROS specific research objectives:

1.Develop a detailed framework for rotorcraft modelling integrating rigid-body and aero-servo-elastic modelling features, capable of dealing with structural or propulsion or mechanical system failures;

2.Understand how humans can safely and efficiently use and be interfaced with rotorcraft technology;

3.Enhance the understanding of the unique and complex aerodynamic environment in which rotorcraft are working, often in hostile conditions of wake encounter threats, undesirable interactions with obstacles, icing and, brownout conditions.

The methodological approach developed within the NITROS training program will be focused on the id entification of the interconnections that exist among these three pillars that are often overlooked during the design. A unique cross-disciplinary research and training program is set up encompassing Control Engineering, Computational Fluid Dynamics (CFD), Modelling and Simulation, Structural Dynamics and Human perception cognition and action. The project is aligned with the European Union endeavor to reduce the rate of aviation accidents by tackling all critical aspects of rotorcraft technology. Twelve young researches will take part in a dynamic network composed by engineering schools (Politecnico di Milano, University of Liverpool, University of Glasgow and Technical University of Delft), and industrial partners that include Leonardo, a rotorcraft manufacturer, Bristow, an important operator, CAA Civil Aviation Authority in UK, a certification body, EUROCONTROL, a regulatory bodies, and two important research centers: NLR The Netherlands Aerospace Centre, specializing in aviation research and Max Plank Institute for Biological Cybernetics which specializes in all aspects related to the human machine interface.

Many research projects have been undertaken in EU in the area of Ensuring Customer Satisfaction and safety (as for example in the 7th Framework Programme (2007-2013): ADDSAFE -Advanced Fault Diagnosis for Safer Flight Guidance and Control, ON-WINGS ONWing Ice DetectioN and MonitorinG System, HUMAN Model-Based Analysis of Human Errors During Aircraft Cockpit System Design, ODICIS One DIsplay for a Cockpit Interactive Solution, SUPRA Simulation of UPset Recovery in Aviation, MISSA More Integrated System Safety Assessment, ALEF Aerodynamic Load Estimation at Extremes of the Flight Envelope, ARISTOTEL -Aircraft and Rotorcraft Pilot Couplings – Tools and Techniques for Alleviation and Detection. However, there has never been a project especially dedicated to treat in a multidisciplinary way the complex subject of rotorcraft bringing together various aspects of different technical fields in order to create an *holistic* approach to the critical area of rotorcraft safety. The goal of NITROS is to “break out” towards a new stage of aircraft safety giving the necessary freedom to the engineer to rethink the solutions used in their multi-disciplinary approach

The network is focusing on twelve research programs focusing on the three main subjects identified that are conducted by highly skilled Early Stage Researchers (ESRs), see Figure 2. Each research program is focused on a problem that affects the safety of the current or innovative rotorcraft configurations. The possible implications of the problem in terms of manufacturing, operations and certification procedures will be thoroughly discussed with the industrial partners. Projects number 1, 5, 6 and 8 will be mainly focused on the analysis of the interaction of the helicopter with the environment. Projects number 2, 4, 9 and 12 will investigate aspects that are more related to aircraft design. Projects 3, 6, 10, and 11 will focus more on aspects related to the human vehicle interaction

## INDIVIDUAL PROJECTS

In this section the twelve research projects are described in more in more detail.

### Simulation and Prevention of Ice Formation and Shedding on Rotorcraft

The requirement for aircraft to be able to fly in any flight condition, every second of the day and every day of the year has never been more prominent than it is now with the increasing demand for fast and reliable transport. With this, the industry faces major dilemmas, that to this day, have yet to be resolved. Such a requirement means that aircraft are being asked to fly in the utmost extremities of the earth, whilst pushing flight boundaries to new levels. These limits are of no greater importance than when it comes to helicopters; aircraft which are designed to operate in high-risk conditions where conventional fixed-wing aircraft cannot and typically where life-saving missions are paramount. Conditions particularly in winter near the poles of the earth, or at significant altitude pose serious problems for helicopters due to the formation of ice on vulnerable regions such as the main rotor.

the presence of ice on the blades of the main rotor can lead to severely damaging consequences to helicopter performance capabilities, becoming a serious threat to flight safety (Re. 11) and are the cause of several aircraft-icing accidents (Ref. 12). It can prompt drastic alterations to the geometry and increase the surface roughness thus, resulting in the increase of drag, reduction of lift and premature onset stall. These aerodynamic changes invariably have implications on the helicopter stability, flight condition, power and torque characteristics and component loading (Refs. 13,14). The build-up of ice on the rotor blades can also alter the rotor trim conditions as well as modifying the inertia and aeroelastic properties of the blades themselves (Ref. 15).

This work will look to take the next step towards providing a deeper understanding into simulating fully three-dimensional unsteady ice accretion on rotorcraft, whilst incorporating the effects of ice shedding before finally developing prevention mechanism and optimizing design to decrease the likelihood of icing accidents. It will seek to understand how the handling qualities and performance of rotorcraft are affected during typical icing environments as well as facilitating aid to pilots to raise their awareness during icing conditions.

### In Service Health Monitoring for Rotorcraft Structures

In recent years, high-performance composite materials have been widely used in industries such as aviation, aerospace, automobile and civil engineering. The unique properties of composite materials such as their high strength-to weight ratio, high creep resistance, high tensile strength at elevated temperatures, and high toughness have been attracting increasing interest in numerous applications in different industries such as the automotive and aerospace industries.

However, there are also many problems with the exploitation of composite materials due to their common disadvantages.

Most important is their susceptibility to initiation and growth of damage in the internal structure in the form of delamination. This type of damage is located between layers of composite material and is initiated by impact. Another type of damage is matrix cracking. These two types of damage can be hidden in the internal structure and may not be visible on the surface of composites. Because of this, a need existed to develop methods to detect and localize these defects.

Structural health monitoring (SHM) is a necessity to address these problems. SHM is referred to the use of on-line sensing and measuring techniques to provide continuous assessment of the working status of engineering structures for damage and degradation monitoring.

Fostered by the nearly immediate success of the on-condition maintenance concept when applied to rotating machinery, like helicopter, different SHM concepts have been developed. As sensor system, to be built within the structure, three main types have been explored and the technology is well known: Piezoelectric wafers, fiber optic Bragg gratings, accelerometers and MEMS (Ref. 16)

Optical fiber sensors embedded in various structures are very useful for strain/temperature monitoring applications in extreme environmental conditions. For example, structural deformations due to delamination and debonding can be monitored, and so avoided, by implementing smart composite structures with embedded fiber-optic sensors.

In composite materials, micro-residual stresses are created during the manufacturing process, due to the mismatch of the physical and mechanical properties of the matrix and reinforcement. The shrinkage of the matrix after curing is also another source of such stresses. In laminated composites, the physical and mechanical properties of each ply are functions of the direction of the reinforcement. This is the source of macro-residual stresses in laminated composites. Also, heat treatment processes after manufacturing, machining and environmental conditions, such as absorption or release of the moisture, are some of the other sources of residual stresses. Although residual stresses can occasionally be beneficial, they are usually detrimental.

The main goal of this study is detecting matrix damage in the particular shape of structure, so the configuration and loading is not so complicated and all of the emphasis is on matrix damages.

### Innovative Design for Tiltrotor Cockpit for the Reduction of Pilot Workload

A tiltrotor is a Vertical Take-Off and Landing (VTOL) capable aircraft and possibly the most researched of the class of Convertible Aerial Vehicle (CAV). The ability of a convertible aircraft to hover like a helicopter and to fly at relatively high cruise speeds and range like a fixed wing aircraft makes it a very effective point-to-point fast means of transportation and it is considered to be the best solution for modern civil transportation system (Refs. 17,18).

The conversion maneuver that allows a tiltrotor to convert from helicopter configuration to a fixed wing configuration is very critical and currently is fully driven by the pilot. Thus, it requires highly skilled pilots and in general the pilot workload is high. In order to reduce the pilot workload and to improve overall safety of the aircraft by avoiding loss of control and Rotorcraft Pilot Couplings (RPCs) (Ref.19), innovation factors are required in the development of new advanced inceptor configurations and innovative FCS algorithms. The development of such novel inceptor configurations and FCS require a high _fidelity flight dynamics model.

### Robust Flight Control of Rotorcraft Immersed in Obstacle's Turbulence

Helicopters are regularly required to perform challenging missions in conned areas and close to obstacles. Search and rescue missions over land and water, urban transport, intervention in natural disasters such as flooding, or earthquake are some examples in which rotorcraft interacts with the surrounding environment. In this situations, performance and handling qualities of the rotorcraft are highly affected by the presence of the obstacles in close proximity. Another prime example is off-shore operation of rotorcraft which is among the most demanding tasks for the pilots. In this case, due to the combination of moving flight deck, flying close to the ship hangar wall, changing speed and direction of the wind and turbulent ship airwake, pilot workload will be significantly increased which may endanger the safety of flight. The ship airwake usually shows a very unsteady behavior, with characteristic frequencies below 2 Hz, while a pilot consciously responds to frequencies in the range of 0.2 to 1.6 Hz (Ref. 20). Consequently, the ship's aerodynamics are expected to affect directly the pilot workload and safety of the operation (Ref. 21). Analysis of safety operating limits for such

**Figure 3. Rotor The rotor-obstacle test setup inside the GVPM wind tunnel (Ref. 22)**

demanding missions needs a series of flight test which are inherently hazardous and extremely expensive. Consequently, development of the helicopter-obstacle Dynamic Interface Simulation is considered as a viable solution. Such a simulation tool could be used to find the optimal trajectory for safe landing and to design and test of new flight control systems.

In this research, it is proposed to develop an aerodynamic model from the scaled experimental wind tunnel tests. The research will define an innovative procedure based on the exploitation of wind tunnel to simulate the flow-field close to the obstacle and the interaction of this unsteady flow field with the one generated by the flying rotorcraft. The Large wind tunnel of Politecnico di Milano (GVPM) with a test room of 14x4 meters allows to perform complex maneuvers of scaled models close to obstacles, measuring velocities and loads on the different parts of the aircraft (Figure 3). This information will be used as source of information for a flight simulator to generate a new trajectory with pilot in the loop. The new trajectory will be reproduced in the wind tunnel in order to verify the results of flight simulation.

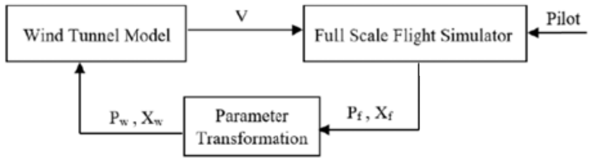

**Figure 4. Closed-loop communication between wind tunnel and flight simulator**

A more challenging approach will consider the possibility to have the wind tunnel in a real time feedback loop with the flight simulator, measuring the components of local air velocity and sending this data to the fight simulator. Then the outputs of the flight simulator (control commands and states) and a new trim condition will be converted for the wind tunnel scaled model and applied (Figure 4).

Finally, the developed aerodynamic model will be used for design and test of a robust automatic controller that is expected to significantly reduce the pilot workload caused by turbulent flow.

### Rotorcraft Wake modelling and Modelling of brown/white-out

This research is supported by earlier studies on wake modelling and wake encounters (Ref. 23-25) and aims to deliver state-of-the-art methods for the simulation of helicopter wakes near ground, obstacles, or mixed with dust or water for the case of brown/white-out. The ESRs 5 and 8 working at Glasgow and POLIMI, are tasked with the modelling of helicopter wakes and brown/white out. Looking at rotor wake modelling, there is a recent trend towards time-accurate simulations using techniques based on CFD. This is a recent development since, in the past, methods like prescribed or free wakes were used. Within the modern CFD methods used for wake modelling, the debate is still on-going as to which approach is best. Several works are based on mesh-less methods that adopt a Lagrangian representation of the flow and grid-based Eulerian methods. Good examples of works in this area include the use of the Vortex Particle Method for the simulation of wakes near ground and obstacles (Ref. 26) as well as Vorticity Transport Models for brown-out (Ref. 27). Based on the current published results, it appears that Lagrangian methods are more efficient and do not suffer from the problem of numerical dissipation that decays the wake strength and is particularly strong with Eulerian grid-based methods. On the other hand, progress with high order spatial discretization methods, parallel computing and adaptive mesh schemes has made it possible to use Eulerian tools for wake calculations albeit with some extra computational cost (Ref. 28). Eulerian methods tend to have better representation of the geometry and loading of rotor blades and fuselage and have more established methods in dealing with phenomena like turbulence, or flow separation and flow unsteadiness near lifting surfaces.

Separate from the issue of wake modelling and its preservation for long distances behind the rotor, is the effort to capture a good amount of flow physics present in phenomena like white or brown-out. In a way the dust or water present around a helicopter involves two flow phases, air-dust for brownout, and air-water/ice for whiteout. This poses modelling challenges if a unified framework is needed for treating with the two-phase flow problem. To date, treating brownout is mainly seen as a single-phase flow problem with very few investigations (Ref. 27) adopting a different approach.

In view of the above, it is the objective of ESRs 5 and 8 to address the two aforementioned problems and provide a step-up in modelling capability. This effort is combined with the work of other ESRs in NITROS so that progress in wake and brown/white out modelling can be used to enhance helicopter safety. Examples include collaborative efforts between ESR 5 and ESR7 to develop wake models that can be used in a flight simulator to assess severity of wake encounters. Much the same way, synergies are seen between ESRs 1 and 8 looking at icing and white-out.

### Development of the Phase Aggression Criterion for Adverse Rotorcraft Pilot Coupling Prediction and Real-time Detection

The requirements for higher speed and longer endurance future rotorcraft will potentially result in higher complexity in the design and operation of such rotorcraft. There is a risk that this additional complexity could lead to an increase in the incidence of unfavourable events such as Adverse Rotorcraft-Pilot Couplings (RPC); anomalous interactions between the pilot and the rotorcraft (Ref.29). RPC events may result in both oscillatory and non-oscillatory from deficiencies in the Flight Control System (FCS), or interactional elements of the vehicle airframe. One form of these RPCs is captured under Pilot Induced Oscillations (PIO). PIOs occur when the pilot inadvertently excites divergent vehicle oscillation by applying control inputs that have phase lags with respect to the vehicle response. PIO phenomena have historically been classified into three categories with reference to the characteristics of the pilot and vehicle dynamics: Cat I linear pilot-vehicle system oscillations (as a result of excessive time delays and control phase lags), Cat. II quasi-linear events with some non-linear contribution, (such as rate or position limiting) and Cat. III non-linear oscillations with transients; such events are usually difficult to recognize and rarely occur, but when they do, they are always severe. It is therefore necessary to design rotorcraft such that they do not exhibit tendencies to PIOs, whatever the triggers and the pilot control actions are.

Real-time metrics have been developed e.g. Phase-Aggression Criterion (PAC) (Ref. 30), to predict and detect these unwanted events. The aim of this research is to build on previous research in this area to produce an effective toolset that can be used during aircraft design and development to reduce the incidence of adverse RPC events; particularly those related to rigid body and aero-servo-elastic RPC events. The planned project will address:

- the prediction and detection of RPCs for response types typical of more advanced helicopter configurations using PAC

- the development and assessment of a cockpit warning system to provide the pilot with useful cueing that an RPC is about to occur

- the development and assessment of a means for alleviating RPC events either before or as they occur.

The benefit to the rotorcraft community will be an improvement in safety by being able to detect an alert the pilot the onset of an RPC resulting, when properly cued, to a potential reduction in pilot workload.

## Mitigation of Airwake Hazards

Helicopters are utilized in a wide range of operational environments especially when flown in support of Search and Rescue (SAR), Emergency Medical Service (EMS) and offshore roles. When flying these types of missions, there are several environmental hazards which can be present that may impact the safety of mission; particularly an inadvertent encounter with an airwake. Whilst there has been a significant effort in the fixed wing community to develop tools and strategies to reduce the threat posed by wake encounters, there has not been a significant corresponding activity in the helicopter community to address this problem. In terms of safety guidance from the regulatory authorities, the UK's Civil Aviation Publication (CAP) 764 (Ref. 31), reports the following "Although research on wind turbine wakes has been carried out, the effects of these wakes on aircraft are not yet known"; this project will undertake research to identify the effects and hazards posed by these encounters.

The project is a collaboration between the University of Liverpool (UoL) and the University of Glasgow (UoG) and seeks to obtain an improved understanding of rotorcraft and pilot behaviour during helicopter encounters with wind turbine wakes. Previous research has been conducted by the team examining the risk posed by rotor and wind turbine wakes on light aircraft, (Refs. 32, 24) but further research is required.

Using the HELIFLIGHT-R flight simulator at UoL (Ref. 33), and the CFD expertise at UoG (Ref. 34), the research will endeavour to identify hazards resulting from helicopters encounters with wind turbine airwakes and develop metrics to assess the resulting risks. The work will define the fidelity requirements for airwake modelling techniques for use in real-time flight simulators and investigate new flight training programmes to improved pilot awareness of hazards. An assessment of the use of on board warning systems to increase situational awareness will be undertaken and it is anticipated that the research will produce safety enhancements through changes in operational procedures, improvements in training and updating of current CAA regulations.

## Enhanced Helicopter Handling Qualities Through Vibratory Loads Exploration

Despite extensive off-line simulations, and numerous pilot-in-the-loop flight simulator trials, handling problems continue to emerge in the very last stage of many helicopter designs, i.e., as "unpleasant surprises" during the flight tests of the prototype (Ref. 35). These problems are dealt with by applying eleventh-hour, ad-hoc flight control system adaptations that, paradoxically, often lead to new, this time highly non-linear pilot/helicopter couplings that may prove to be even more difficult to predict and eliminate than the original ones (Ref. 36). In some cases, it is advised that these systems are not to be used in certain phases of flight, as they may hinder pilots more than they help them. In many cases, the flight envelope is simply reduced, keeping the newly-designed helicopter from meeting its original requirements. Unmistakably, high-performance helicopter design has become an arduous process, regularly leading to surprises, involving "patches" to safety-critical systems, and frequently requiring many more iterations than expected, all contributing to very high costs (Ref. 37).

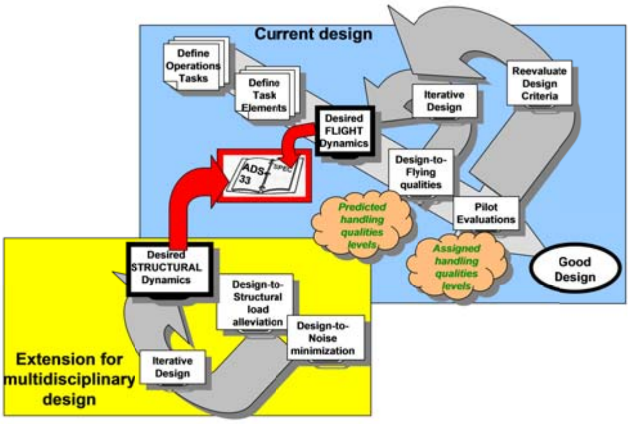

**Figure 5. Current practice in design to flying qualities**

Figure 5 presents the current practice in FQs design (blue block) as performed during the phase of Preliminary design (this means that the design solution has already been passed the conceptual design and rotor + fuselage basic parameters have been chosen). Looking at Figure 5 one can see that firstly a database of tasks and environments are defined based on specified customer requirements. Herein constrains imposed on the maneuverability (how easily can the pilot guide the aircraft) and agility (how quickly can the pilot change the flight direction) can play an important role. The tasks are usually broken down into task elements to simplify the design. Then the design-to-flying qualities process is initiated and has the main goal to develop the control laws that meet the desired dynamics and to finally define the so-called predicted levels of HQs. Then, the predicted levels of HQs are verified during formal handling qualities evaluations with test pilots flying the database of missions in suitable test facilities (for example ground-based simulators fixed or full-motion) providing evaluation comments and subjective ratings in the Cooper-Harper handling qualities rating scale (Ref. 38).

More and more evidence exists indicating that many times during actual design large differences appear between the predicted and the assigned levels of handling qualities. Kolwey in Ref. 39 for example enumerated an extended list of cases from current practice where the unpredicted effects of the helicopter structural dynamics on the flying qualities design affect in real practice the helicopter maneuvering performance, limiting its operational flight envelope (OFE). Operational Flight Envelopes represent charts determined during flight tests of a new configuration giving the limits (airspeed, altitude, load factor, rate-of-climb, turn rate, etc.) within which the helicopter must operate in service. These charts are determined using the ADS-33 handling qualities criteria (ADS-33 gives safe clearance for all maneuvers to be done in the OFEs). Kolwey (Ref. 39) underlines that the current experience demonstrates that maneuvers currently flown in the OFE could exceed the helicopter structural limits and recommends maximum carefulness in applying the ADS-33 criteria as they are not sufficient in predicting the rotorcraft structural limits. Referring to the shortcomings in ADS-33 it looks like a fundamental tension that seems to be unrecognised can be proved among engineers when using ADS-33. This tension arrives because, although ADS-33 proposed innovative criteria and missions transposing the helicopter limits to new, unreachable borders, the proposed criteria are characterizing only the performance of both helicopter and pilot, lacking an adequate knowledge of helicopter structural and vibratory loads. This lack of knowledge is probably due to the fact that in the past, the missions of the older helicopters were not so demanding. This is no longer the case for the agile helicopters of the present.

In two other extensive reviews on challenges in handling qualities, both Padfield Ref. 40 and Michell et. al. Ref. 41 pointed out that one of the major deficiency in HQs is related to the limited knowledge existing on the vehicle's vibratory effects on the pilot workload. Indeed, especially for helicopters, vibrations have been and remain a problem. The inherent tendency of a rotorcraft to generate periodic forces on the rotor which are then transmitted to the fuselage is an extremely difficult problem to deal with. It is well known that contemporary helicopters still reach vibration levels higher than 0.1g which make them yet not really comfortable while a desirable level of 0.02g should be reached (i.e. 5 times lower) (Ref. 42). Especially when flying difficult operations in obstacle rich environments and adverse weather conditions, strong vibratory loads and cross-coupling effects could develop on the helicopter structure leading rapidly to pilot overload and degradation in performance. In an early experiment at NASA Langley Research Center six test pilots were asked to describe how high vibrations are influencing their decisions in flight (Ref. 43). The results showed that the pilots perceive high vibrations as high workload for at least two subtly different reasons: 1) one reason was that cockpit vibrations simply have a negative impact on the level of HQs perceived by the pilot; 2) the other reason was that, for some pilots, vibrations actually result in involuntary control inputs.

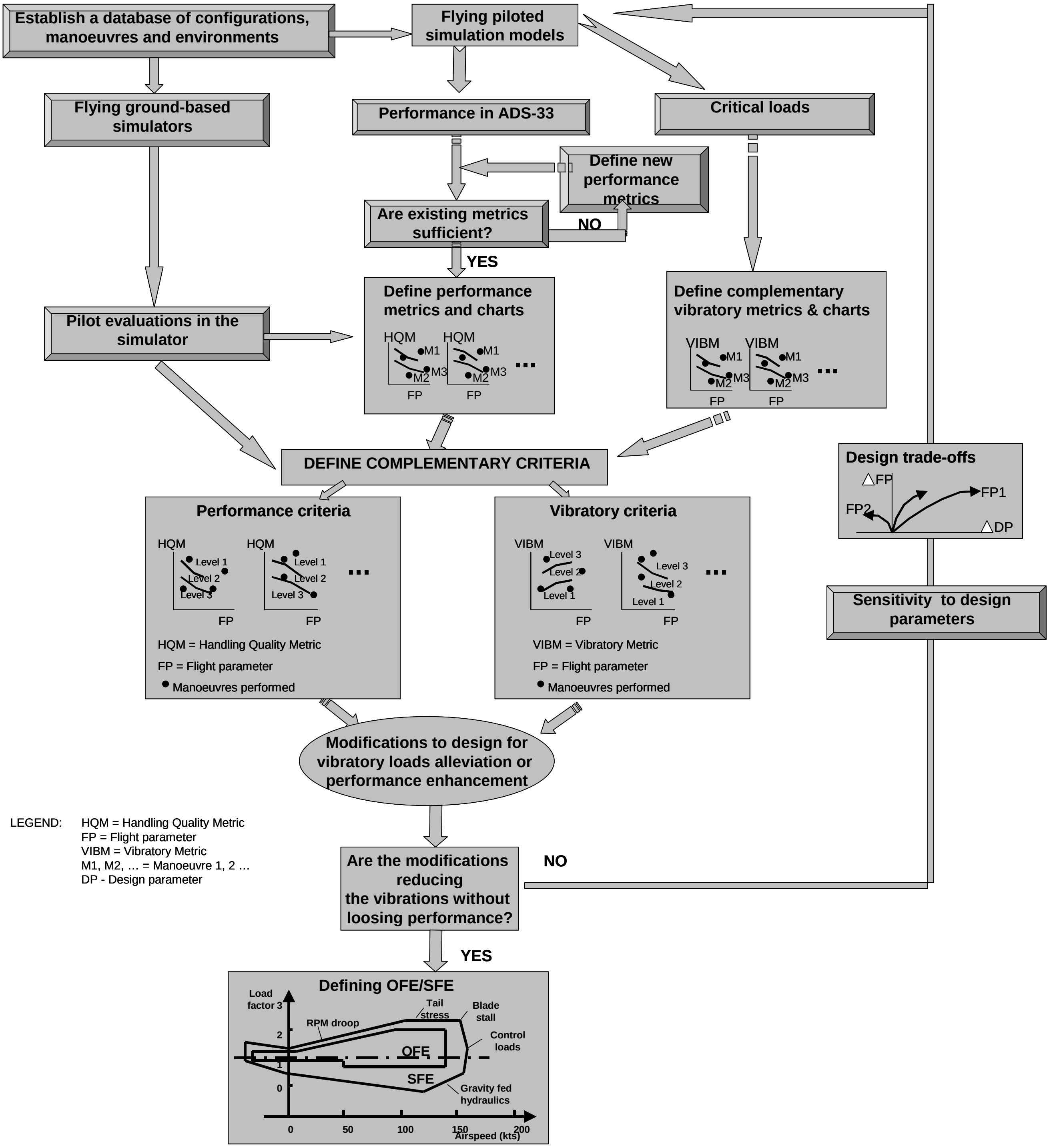

**Figure 6. Defining new handling qualities/vibratory criteria for the designer**

The question is then how can one tackle at the same time the aircraft performance and the vibratory loading problem? Using optimization techniques seems not the appropriate way to answer this question since the models used are increasing in complexity and add more difficulties and time to be solved. The goal of this project is to develop new tools to help the designer to integrate in an early stage to optimize the vibratory loads, noise and flying qualities. Therefore, we helicopter performance, vibratory activity and pilot workload necessary when executing specific missions. Figure 6 illustrates a road map for the research conducted by the researcher in NITROS for defining complementary HQs-vibratory criteria. First, a database of representative helicopter and tilt-rotor configurations (such as UH-60A Black Hawk, Bo-105, Puma SA-330, Lynx, Bell XV-15) will be collected in cooperation with the industry, universities and research institutes. For these configurations a database of specific maneuvers, missions and environments covering the full range of cases expected in operation will be defined. The missions are designed from small tasks (maneuver samples) such as climbout, cruise, descent, turn, landing, hover, etc. that feature essential aspects of pilot skills, task difficulty and workload. Using these simulation models in the next step the research will simulate the defined maneuvers and missions and measure on the one side the performance achieved according to ADS-33 metrics and criteria and on the other side the critical vibratory loads (for example as the loads achieving the highest amplitude). Sometimes it can appear that ADS-33 does not possess the proper metrics to characterize the maneuver performance. In this case, new metrics will be searched that are more appropriate to the maneuver performed. Having defined the proper metrics to characterize performance for every maneuver, researcher A will then connect them to equivalent vibratory metrics defined as complementary to the performance metrics. The vibratory metrics are characterizing thus the vibratory activity on every maneuver performed. At the end of this step, the researcher has at his/her disposal sets of complementary performance/vibratory metrics reflecting the couplings existing between performance achieved/ structural loads/ task complexity when executing different maneuvers. These new performance/vibratory metrics can be plotted in charts characterizing the rotorcraft response from pilot point of view. Then, to become useful criteria, boundaries for Levels 1,2 and 3 of HQs need to be assigned to these charts.

### Revealing adverse Rotorcraft Pilot Couplings induced by Flight Control Systems

When designing flying qualities, one interesting field that needs attention is that of prevention of the so-called pilot-induced oscillations phenomena (lately renamed as “pilot-aircraft couplings” to indicate that the pilot is not the responsible part in such cases). A pilot induced oscillation is defined as “an inadvertent, sustained aircraft oscillation as a consequence of an abnormal joint enterprise between the aircraft and the pilot” (Ref. 44). It actually happens when, due to a trigger event, a vicious circle is formed between the pilot and the aircraft, the response of the rotorcraft being reinforced by the pilot input. PIO’s have occurred during the development process for almost every new airplane. The oscillations developed may vary from a very temporary, easily corrected mild oscillation to a terrifying large amplitude oscillation with catastrophic consequences. Frequently the severity of the oscillations is sufficiently low so that the PIO can be detected and eliminated with little or no public acknowledgement of the event. These PIO’s are the so-called “Category I linear PIO’s” and are associated with a linear and time-stationary behavior of the pilot and control system. They are eliminated without difficulty by loosening control. However, occasionally the consequences of the PIO’s are such that they become headline news. These PIO’s correspond to “Category II Quasi-linear” and “Category III Non-linear” and are mostly associated with non-linear effects in control system. Usually, in such cases, the active flight controllers, although including actuators to damp any undesirable motion, could not cope anymore with the intensity of the motion and get saturated – the so-called “actuator saturation” phenomenon. For good literature on non-linear PIO’s one can consult Refs. 45-51. Category II and III PIO’s are difficult to predict and eliminate during design. Famous categories II PIO encountered with helicopters in the mid 80’s was with Sikorsky CH-53 heavy lift helicopter (Ref. 44). This PIO created a high-level attention in the US Navy and showed as several dramatic incidents which occurred over a period of years (1978-1985), including some high-visibility events in which catastrophe was avoided only by dropping the load. The PIO manifested as severe oscillations when the helicopter was executing precision hover tasks with large sling loads suspended on it and was caused by the pilot interaction with the lower frequency flexible modes. The extra dynamics due to the sling load were not the trigger factor, it was the much higher sensitivity to cyclic control associated with the increased collective needed to support the load.

While much work has been performed for unmasking Cat I and II PIO, predicting Cat III PIO is still a challenge (see review papers of Pavel et. al. Refs. 52, 53, 54) A researcher in NITROS will investigate precisely this area. The most significant nonlinearities considered in terms of PIO relate to rate limits and saturations that occur naturally on control actuators and those that are intentionally designed into the control system, in the form of command or software rate limits. The effect of these nonlinearities changes with several factors, ex. pilot input bandwidth, the amount of rate limiting experienced, and the consequences of reaching the rate limit. There are also other nonlinear elements in the control system (such as breakout and hysteresis or in the command shaping, effects of gain scheduling, mode switching, and aerodynamic nonlinearities) that may contribute to PIO; many of these are yet not well-documented and the goal is to enrich this area. The researcher may consider also model based nonlinear control systems, such as nonlinear dynamic inversion (NDI) or backstepping methods. In such methods, the inner loops of the control system plus aircraft are made linear (or with only stabilizing nonlinear terms in the case of backstepping), with the aim of making the aircraft easier to control for the pilot in the outer loop. This linearization is performed by multiplying the system with an inverse of the modelled system dynamics. However, when there is a mismatch between the on-board model and the real aircraft dynamics, or when there are time delays in the system, then the inversion is not perfect and nonlinear terms in the original dynamics are not fully cancelled. On top of that, additional possibly unstable dynamics can be introduced by the model mismatch. In the proposed research the influence of these model mismatches on A/RPC’s will be investigated.

## Understanding the use of automation in helicopters

Next to the flight control system effects, one researcher in NITROS will concentrate on the automatic flight control systems for helicopters. While vast improvements in basic helicopter design and avionics have greatly increased the safety of helicopters, there are still many catastrophic incidents due to automation in the cockpit. The paradigm of automation is that it functions best when the workload is light and the task routine; when the task requires assistance or workload is high, the automatic equipment seems of least assistance. This is why, one researcher of NITROS will take the task of improving automation in the helicopter cockpit. Particularly, the aim is to apply the so-called concept of “Ecological Interface Design” (EID) to helicopters. EID is a framework for the design of interfaces of (complex) technical systems. It focusses on the work domain of the system, aiming to visualize its specific constraints. These constraints are independent from specific control strategies and their implementation, e.g. via manual control or automation. In EID the idea is that eliminating totally the humans from the system is wrong: humans were and continue to be an essential component in every technical system, as they can bring adaptivity and creativity that can enhance the system resilience. Therefore, rather than striving exclusively to replace human weaknesses with technical systems, the goal should be at exploring ways in which technology can facilitate human adaptivity and flexibility to cope with unforeseen events (i.e, to enhance resilience). Recognizing this role of pilot in the cockpit, the concept of EID was introduced by Rasmussen and Vicente Refs. 55,56.

In contrast with user- and technology-centered approaches that put the emphasis on either the human or on the technology, EID starts by focusing on the work domain (i.e., “ecology”). The goal of EID is then to facilitate coordination between humans and automatic systems by making interface representations that reflect the structure of the work domain in ways that support human skill-, rule-, and knowledge-based problem-solving activities. However, the main question in an EID system is still how much “freedom” should be given to the human and how much to the automatic system. In other words, the question is what should be the interrelation between the human and the technology for optimum safety (Ref. 57, 58). Starting from the theoretical background and the understanding of the application of EID in fixed-wing aircraft, the goal of the researcher in NITROS will be to apply the EID concept when the helicopter is flying a range of missions such as: 1) autorotation after partial or total engine failure and 2) operations on an oil deck in the sea in nominal and off-nominal weather conditions.

## Alleviating flight simulator negative transference for helicopter operations

Going from automation in the cockpit to flight simulators is the last step that NITROS will take in its research. One researcher in NITROS will consider the transfer of training from the simulator to the real world. In general, transfer of training is “the combined result of input factors (characteristics of the trainee, training design, and work environment), the amount learned in training, and the conditions surrounding the transfer setting.” Transfer of training is negative when a training situation hinders the pilot performance in the real world. In the past, several research studies indicated that successful transfer did not require specifically high-fidelity simulators or whole-task training, thus reducing simulator development costs (Refs. 59, 60). However, up to the present, researchers failed to report sufficient detail regarding research methods, training characteristics, and simulator fidelity. The goal of this researcher will be to understand the relation between the pilot transfer of training in the simulator and the mathematical model of the simulator. In other words, the aim will be to understand the impact of mathematical model variables on transfer of training. Linking the physical cause and effect of model variables to the transfer of training will be the key for the development of this relation.

For example, to characterize the helicopter Dutch roll behavior, usually the simulator developers perform a special a test designed to demonstrate that the Dutch roll period and damping in the simulator are close to the flight data according to CS FSTD-H simulator standard. For the SuperPuma helicopter tests, pilots did not especially complain about this unstable mode by flying in Visual Meteorological Conditions (VMC) and concluded that the simulator was handling like the real helicopter. However, when conducting the same test in Instrument Meteorological Conditions (IMC), the pilots complained that the model was too unstable and too difficult to manage. For both tests the flight loop model was unchanged and only the external environment was modified. When flying in VMC, the pilot is helped by good visual cues whereas he has to rely on the instruments information only when flying in IMC. Even if the pilot was taught not to take care of the accelerations, different feelings in the simulator and in the real aircraft made his task more difficult. He reported he was unable to stop the Dutch roll oscillations and asked for a higher damping to reproduce the helicopter behavior (Ref. 61). Therefore, the damping of the Dutch roll mode had been intentionally set at the very upper limit of the simulator level D requirement (the simulator was set to more unstable than in flight), even if it was possible to achieve a better match with the flight data. This example shows that although a pilot is unlikely to be able to distinguish between the different physical contribution of the model to the overall Dutch roll characteristics, he may be aware of the mismatch in the lateral acceleration and therefore sideslip and these characteristics are important for transfer of training. This is an example of the compromise that one needs to do in the simulator in order to ensure positive transfer of training.

## CONCLUSIONS

Safety of rotorcraft flights improved significantly over the last few years, however there is sill a gap to be filled to reach the level required to expand the usage of this types of vehicle.

The NITROS project through the twelve presented projects will try to reach several goals: first to obtain a significant reduction of the accident rate up to especially for future rotorcraft designs through the definition of new technologies but also new design methodologies and testing methodologies and operational standards; secondly, to train the next generation engineers to avoid overlooking the impact that their design choices may have on flight safety, fostering the investigation of safety issues on innovative vertical take-off configurations that may assume an important role in the future European transport network.

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