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ROTORCRAFT-PILOT COUPLINGS: ANALYSIS AND DETECTION IN A SAFETY ENHANCEMENT FRAMEWORK

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Abstract

Nowadays, the complexity of high speed civil transport and highly-augmented rotorcraft, has led to an increase in the chances of encountering unwanted unstable phenomena, such as the so called Aircraft/Rotorcraft-Pilot Couplings (A/RPCs) or Pilot-Induced Oscillations (PIOs), whose unpredictability has given rise to a serious problem concerning the safety of a mission. When talking about PIOs, McRuer defined them as "inadvertent, sustained aircraft oscillations which are a consequence of an abnormal joint enterprise between the aircraft and the pilot". However, A/RPCs, these undesirable events associated with the interaction between pilot and aircraft, have become diverse and more complex than those encountered in the past. At the moment, there are different methods available to prevent and detect Cat. I/II A/RPC, but particular interest has recently arisen in this topic for flight simulation applications as any enhancement of these tools in order to accurately and objectively predict, detect (in real-time) and alleviate RPCs will be greatly welcomed. One of the main questions to be answered through the efforts carried out within this work is related to the better *detection in real-time* of embedded tendencies to RPCs in modern aircraft. To answer this question, initially an assessment of the efficacy of the Phase-Aggression Criterion (PAC), which has been designed a few years ago at the University of Liverpool, will be undertaken either: as a means of *alerting the pilot* to conditions likely to lead to the onset of a PIO; or, given that the time available for the pilot to counteract may be extremely limited, as a means to *assist him/her in alleviating* (automatically) the PIO condition itself. Preliminary results from flight simulation trials to explore how best to achieve this will be reported. Moreover, this work will report on the development of PAC boundaries for more *highly augmented response types*. Furthermore, as classified by McRuer, Cat. III PIO, which is nonlinear in essence, is the most complex one. However, the researches on Cat. III PIO are rare. This paper will reveal some elementary results of Cat. III PIO. Since there is no existing method used for predicting and detecting Cat. III PIO, this paper utilized the characteristics of PIO, such as the amplitude, the oscillation frequency and ultimate tendency of key aircraft response states to judge Cat. III PIO preliminarily. By using this elementary judgment of PIO, we studied the following factors: time delay of pilot input and helicopter main body, actuator position saturation, actuator rate limit and SCAS control authority in triggering PIO. Results show that PIO induced by actuator position saturation, actuator rate limit and SCAS control authority can be regarded as Cat. III PIO as the variation of these factors can be viewed as a kind of transition of effective controlled vehicle dynamics. These kinds of transition can cause a mismatch between the effective controlled vehicle dynamics and pilot control strategy, which is the main cause of Cat. III PIO.

NOMENCLATURE

A_G	Aggression, deg/s^2
H_s	Control Gearing, deg/s/in (for RC) - deg/in (for ACAH)
$T_{p_{PK1}}$	Time of last roll peak rate, s
$T_{q_{PK1}}$	Time of last pitch peak rate, s
$T_{\delta_{PK1}}$	Time of last control peak, s
$T_{p_{PK2}}$	Time of current roll peak rate, s
$T_{q_{PK2}}$	Time of current pitch peak rate, s
$T_{\delta_{PK2}}$	Time of current control peak, s
t	Time, s
Φ	Phase Distortion, deg
$\delta_{\Theta_{1c}}$	Lateral Pilot Control Input, in
$\delta_{\Theta_{1s}}$	Longitudinal Pilot Control Input, deg

Θ_{1c}	Lateral Swashplate Deflection, deg
Θ_{1s}	Longitudinal Swashplate Deflection, deg
τ_p	Time Delay, s
θ	Pitch Angle, rad
ϕ	Roll Angle, rad
q	Pitch Rate, rad/s
p	Roll Rate, rad/s
V	Forward Speed, m/s
H	Altitude, m
u	Forward Speed along X-axis of Body Frame, m/s
w	Forward Speed along Z-axis of Body Frame, m/s

Subscripts

ol	Open Loop
cl	Closed Loop
p	Pilot
PK_1	Last peak
PK_2	Current peak
Θ_{1c}	Lateral Control
Θ_{1s}	Longitudinal Control

Acronyms

ACAH	Attitude Command Attitude Hold
ADS	Aeronautical Design Standard
ARISTOTEL	Aircraft and Rotorcraft Pilot Coupling: Tools and Techniques for Alleviation and Detection
A/RPC	Aircraft/Rotorcraft Pilot Coupling
DVE	Degraded Visual Environment
FBW	Fly-by-wire
FCS	Flight Control System
HQ	Handling Qualities
MTE	Mission Task Element
NDI	Nonlinear Dynamic Inverse
PAC	Phase Aggression Criterion
PIO	Pilot Induced Oscillation
PVS	Pilot Vehicle System
RC	Rate Command
RLE	Rate Limiting Element
ROVER	Real-Time Oscillation Verifier
SCAS	Stability and Control Augmentation System

1. INTRODUCTION

Aircraft/Rotorcraft Pilot Couplings (A/RPCs*) have become very different and far more complex and varied from those encountered in the past[1]. Generally, A/RPCs are defined as "inadvertent, sustained aircraft oscillations which are a consequence of an abnormal joint enterprise between the aircraft and the pilot"[2,3]. In other words, they are undesirable and hazardous phenomena that are associated with pilot-aircraft interactions. It seems that there is a serious problem of safety regarding unpredictable A/RPC, especially in future large/flexible aircraft, high speed civil transport and highly-augmented rotorcraft, therefore also involving Handling Qualities studies[4,5]. At the moment, we do not possess the proper tools to prevent, detect, and alleviate A/RPCs, especially in future vehicle configurations[6]. Clearly, there is room for improvement in this area.

At the end of 2016, a research activity was launched in the European Union under the umbrella of the Marie Skłodowska-Curie Joint Doctorates Programme âĂŞ Network for Innovative Training on Rotorcraft Safety (NITROS) project (`https://www.nitros-ejd.org/`). Bringing together a number of research centres and universities in Europe, NITROS is focused on rotorcraft safety, preparing a new generation of talented young engineers, to doctoral level, to become future specialists in rotorcraft safety issues. One of the areas that need refocus and better tools relates to RPCs. NITROS addresses two main questions on RPCs:

1 How can one better predict embedded tendencies that predispose the pilot-aircraft system towards RPC occurrences in modern aircraft equipped with a partial or total fly-by-wire flight control system (FCS)?

2 How can one better detect in real time embedded tendencies to RPCs in modern aircraft?

For the first question, the goal is to concentrate on flight regimes where cliff-like phenomena are most likely to appear. For example, "high gain" tracking tasks where the non-linear rotorcraft dynamics play an important part in the FCS design as well as effects of FCS mode transitions on handling qualities can be used as cases for embedded RPCs of modern aircraft. The paper will give an example of a case where a Category III non-linear Pilot-Induced Oscillations (PIO) – i.e. PIO associated with non-linear flight control system effects – is triggered, determining how these nonlinearities change with different factors, e.g. pilot input bandwidth or the amount of rate limiting experienced, and the consequences herein on the RPC. The most significant nonlinearities considered in terms of PIO in this paper will relate to rate limits and saturations that occur naturally on control actuators, but AFCS-induced saturations can be considered as well.

For the second question, the initial goal will be to build on the work of Ref.[7] to assess the efficacy of the Phase-Aggression Criterion (PAC) either: as a means of alerting the pilot to conditions likely to lead to the onset of a PIO; or, given that the time available to do this may be extremely limited, as a means to assist the pilot in alleviating the PIO condition itself. Initial results from flight simulation trials to explore how best to achieve this will be reported. PAC has so far been developed for rate command systems in the pitch and roll axes for command

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*In the paper both terms of A/RPC and PIO will be used as terminology paths with time delays in them and in the roll axis for command paths with rate limiting included. The paper will report on the development of PAC boundaries for more highly augmented response types.

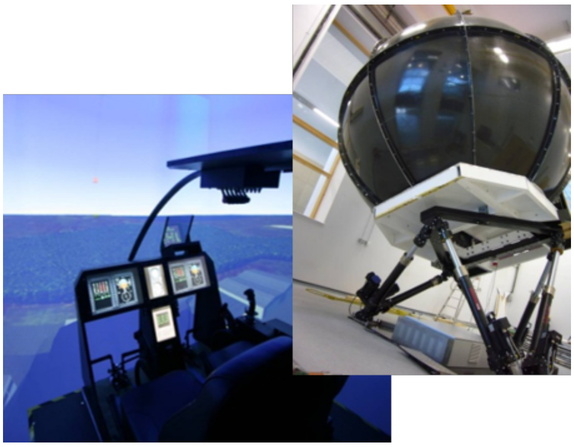

Figure 1: Heliflight-R, inside and outside views

1.1. Research goal

The research goal is to extend and improve existing procedures used to predict Category III aircraft/rotorcraft pilot couplings (A/RPC) and give guidelines to the designer how the automatic flight control system (AFCS) can be adjusted to minimise A/RPCs. For modern aircraft equipped with a partial or total fly-by-wire flight control system (FCS), it is important to understand the effects of nonlinear flight control systems and their role in triggering Cat. III A/RPC, in combination with the influence of the nonlinearity in the helicopter itself, such as the actuator dynamics. As the level of automation is likely to increase and full-authority Fly-By-Wire systems are likely to be more commonplace in operational rotorcraft (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 Cat III RPCs are expected in the future.

This paper is structured as follows. First, after introducing the subject of the research and the research goal, a description and insight about PIOs will be reported. Afterwards, the method on which the research is based is introduced. Then, the results are reported and in the end, an overall discussion on this study is held, conclusions are drawn and a future planning is proposed.

2. BACKGROUND AND INSIGHT

2.1. General Characteristics of PIO

Reference[8] described 10 different kinds of definition for a PIO. The most classic definition belongs to McRuer "PIO is a sustained or uncontrollable unintentional oscillation resulting from the efforts of the pilot to control the aircraft." Its ultimate tendency may be either constant-amplitude, convergent or divergent with time. PIO may contain any number of cycle of oscillations and there is no minimum number to declare it a PIO. PIO may occur at a certain range (1 rad/s to 8 rad/s), but frequency alone cannot determine whether an oscillation is a PIO or not. Furthermore, amplitude of the aircraft response state is another important factor to determine whether an oscillation is a PIO. Sometimes small-amplitude oscillations may be regarded as a "mild" form of PIO and may not even be judged as PIO. Another way to judge the severity of PIO is by looking at the extent of completion of the task. PIO that interferes with, but does not prevent, performance of a primary flying mission task is a "moderate" PIO. PIO that prevents performance of the task, or that requires the pilot making an attempt to abandon the task to stop the oscillations, is a "severe" PIO.

2.2. PAC Background

The aim of the Phase-Aggression Criterion (PAC) is to predict and detect in real-time adverse rotorcraft-pilot couplings (ARPC). Up to now it has been developed as a post-processing tool, i.e. processing data resulting from simulated flight trials to observe potential RPC susceptibility. Furthermore, apart from off-line detection, PAC has been developed to predict PIO events (always during off-line simulation); the next step is to detect "on-line". It may simply be that detecting and indicating to the pilot a PIO tendency is efficiently enough to alleviate it, but it may be that, upon detecting, the control system needs to intervene to reduce the oscillations and keep the pilot workload at a reasonable level.

PAC calculates time varying parameters, such as Phase Distortion (Φ) and Aggression (A_G), based on data traces related to pilot input (lateral and longitudinal stick deflection) and vehicle output (roll and pitch rate). PAC returns metrics that can be translated into PIO or RPC susceptibility.

The reason why we need a real-time metric is because sometimes pilots do not recognize sustained PIOs, and real-time detection can be used to monitor the pilot-vehicle system (PVS) during critical flight test evaluations.

After a number of simulated test campaigns performed at the University of Liverpool[9,10], different PAC charts have been produced, for different control axes (longitudinal and lateral) and for different PIO categories (PIO Cat. I and Cat. II types), along with the reproduction of the PIO severity boundaries defined from a combination of subjective and objective evaluations[11]. Therefore, the PIO incipience was engineered for a number of tasks, essentially: pitch tracking (with time delays and rate limiting elements), precision hover (with only time delays) and roll step.

2.3. Description of Cat. III PIO

Cat. III PIO are essentially nonlinear Pilot-Vehicle System Oscillations related to transitions[12]. These PIOs fundamentally depend on nonlinear transitions in either the effective controlled element dynamics, or in the pilot's behavioral dynamics[12]:

- The shifts in effective controlled element dynamics may be associated with the magnitude of the pilot's output, or may be due to internal changes in either control system or aerodynamic/propulsion configurations, mode changes, etc.[12].
- Pilot transitions may be shifts in dynamic behavioral properties (e.g., from compensatory to synchronous), from modifications in cues (e.g., from attitude to load factor), or from behavioral adjustments to accommodate task modifications[12].

Essentially, changes in controlled element dynamics and pilot dynamic behavioural properties are not isolated but interconnected. Pilot transitions may appear after shifts in effective controlled element dynamics occur. For example, in normal circumstances, when the vehicle mode changes, the pilot control pattern (e.g., from compensatory to synchronous) and cues (e.g., from attitude to load factor) and pilot control strategy may also change accordingly. However, if there is a mismatch between the pilot transition and controlled element dynamics transition, the probability that Cat. III PIO will occur is increased. Due to the nonlinearities and the fact that dynamics or tasks change, A/RPC occurrences in this category are most difficult to analyze offline. Criteria specifically designed for this category are practically non-existent[12]. It is the goal of this research project to design criteria for Cat III PIO specially at rotorcraft.

2.4. Factors contributing to Cat III PIO

The focus of Cat III PIO relates to transitions in effective controlled element dynamics, pilot transition and mismatch between their transitions. Therefore, factors contributing to Cat. III PIO can be analysed from the following two aspects:

A Pilot-centered transitions
Pilot-centered transitions can include: shifts in cues (e.g., from attitude tracking to load-factor); shifts in behavioral mode (e.g., from pursuit to compensatory, or precognitive to pursuit to compensatory); and shifts in effective pilot equalization dynamics (e.g., from compensatory to synchronous or pure gain). Past experience indicates that the most significant are the shifts from compensatory to pure gain and, perhaps, the shifts in cues from attitude to load-factor. Such shifts have been found to be especially important for fixed-wing aircraft and involve flexible modes and neuromuscular couplings (e.g., limb-bobweight effects)[12].

B Vehicle-centered transitions
For fixed-wing aircraft, the transitions in effective controlled element dynamics can include: sudden changes in thrust, flap settings, stores release, flight control system modes, etc., or the rapid but somewhat less sudden changes such as increased mass introduced by refuelling mission, drastic trim changes in sudden decelerations, etc., can cause major changes in the effective controlled element dynamics. These can create great challenges for pilot adaptive behavior especially when they occur suddenly. These kinds of transitions in effective controlled-element dynamics have become more prevalent since advances in flight control system technology have made possible new modes designed on purpose help to improve overall performance[13]. Moreover, unpredictable failures of the aircraft systems (engine, control system, hydraulic system, actuator system, sensor system etc.) lead to sharp aircraft disturbance and/or the modification of aircraft handling qualities (e.g. dynamic characteristics, control sensitivity, feel system characteristics etc.). They cause changes in the effective vehicle dynamics which lead to a mismatch between the pilot control strategy and the aircraft dynamics[1].

For rotorcraft with fly-by-wire 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[14,15]. The same situation happened for the fixed wing F-8 DFBW (Digital Fly-By-Wire) test aircraft[3]. The YF-22 APC case and the XV-15 and later 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[16].

2.5. Factors contributing to Cat III PIO at rotorcraft

The main factor contributing to Cat III PIO in rotorcraft is the inherent delay between pilot input and the rotorcraft body response. The higher order dynamics of rotorcraft, compared to fixed wing aircraft, gives rise to delays of up to 100ms for conventional controlled rotorcraft and up to 250ms for rotorcraft augmented with FBW AFCS[17,18]. This input-response delay is built up from several components: rotor response delay due to flapping dynamics, actuator delay, digital signal processing and filtering delays.

The result of this delay is a reduced bandwidth and a reduced phase margin which can lead to poor handling qualities, which is why the US Army's rotorcraft handling Qualities Requirements Standard, ADS-33D[5], consideres bandwidth and effective time delay as two of the most important flight control design parameters.

3. METHOD

3.1. Pilot-Vehicle System Model

The incipience of PIOs is something difficult to predict and it is also really difficult to understand what is the cause behind them. It is without a doubt doubtlessly strongly related to the Pilot-Vehicle System, and essentially to the interactions between pilot and vehicle. Historically it has been demonstrated that the main causes triggering a PIO are the amplitude of the pilot control inputs during the completion of a task, the phase delay between pilot input and aircraft response, and the frequency at which these oscillatory phenomena occur.

Figure 2, shows a block diagram representing a closed-loop manual control task. Manual control tasks are usually designed to control a single axis (roll degree of freedom in this example), hence only one specific plane (here lateral), along with its variables, is considered. It is clear how the (human) controller and the aircraft dynamics have key roles in the successful completion of the task.

In this example, the variables in question are the system input (trim bank angle) ϕ_{trim}, the lateral pilot control input $\delta_{\Theta_{1c}}$, the lateral swashplate deflection Θ_{1c} and the system output (actual bank angle) ϕ.

3.2. PAC Overview

The Phase-Aggression Criterion[7,9,10,11,19] originates from the usefulness of other methods for observation and detection of RPCs, such as the Pilot-Inceptor Workload proposed by Grey[20,21] and the Real-Time Oscillation VERifier (ROVER) developed by Mitchell[22]. The novelty of the PAC with respect to the previous methods resides in the fact that it provides an indication of the severity of the PIO event and can be used, by means of an in-cockpit device, as a warning system.

Figure 3 shows an example of the time history of two signals representing the pilot input and the rotorcraft response.

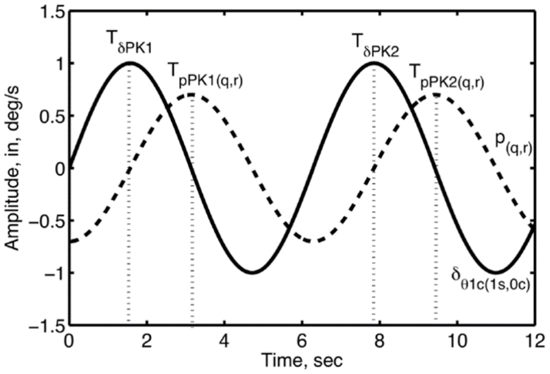

Figure 3: Time history of input-output signals for the determination of time peaks in order to calculate PAC parameters

Considering motion in the lateral axis, the Phase Distortion (Φ) parameter, introduced in the previous chapter, can be calculated as shown in Equation (1).

$$\Phi = 360 \cdot \frac{T_{p_{PK2}} - T_{\delta_{PK2}}}{T_{\delta_{PK2}} - T_{\delta_{PK1}}} \tag{1}$$

Φ is basically given by the fraction of the difference between the current time peaks of vehicle rate response and pilot input and the corresponding period of one oscillation of the pilot input, everything multiplied by 360 degrees. The Phase Distortion is an indication of the amount of phase delay between pilot input and aircraft response (e.g. a Φ of 90 deg means aircraft response out of phase with respect to the pilot input). Each time a new Φ is calculated, an associated A_G can be computed. Aggression (A_G) can be considered as a measure of pilot control activity, i.e. how intensively the pilot is working to

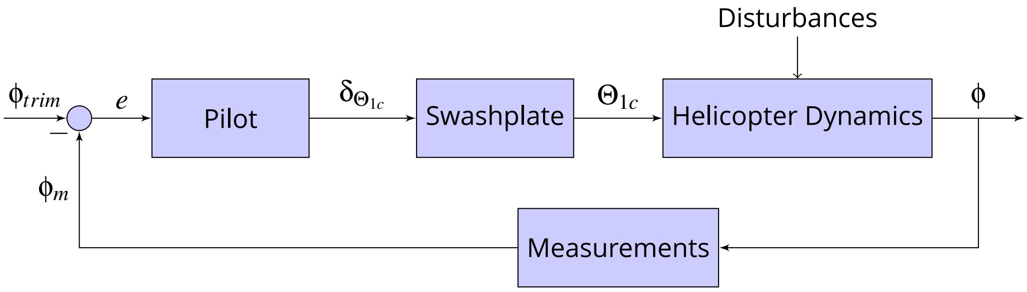

Figure 2: Schematic representation of a closed-loop manual control task in the roll axis

achieve precision in his/her task. In other words, the higher the A_G, the larger and faster the control inputs. The algebraic definition of A_G (in the roll axis) is presented in Equation (2) and shows that it is basically the integral of the pilot control rate over the sampling time period, divided by the time period of the oscillatory cycle (i.e. the temporal integral mean of the pilot control rate over the sampling time period) and multiplied by H_s.

$$(2) \quad A_G = H_s \cdot \frac{1}{T_{pPK2} - T_{pPK1}} \cdot \int_{T_{pPK1}}^{T_{pPK2}} |\dot{\delta}_{\theta_{1c}}(t)|dt$$

The term H_s represents the so-called control gearing and describes the vehicle attitude rate with respect to the pilot control input. In the previous research H_s was used for Rate Command (RC) systems and its definition is given by Equation (3)

$$(3) \quad H_s = \frac{\Delta p}{\Delta\delta_{\theta_{1c}}} = \frac{\theta_{1c}}{\Delta\delta_{\theta_{1c}}} \cdot \frac{\Delta p}{\theta_{1c}}$$

For a RC system the units of A_G are deg/s^2 since the units of H_s are $deg/(s \cdot in)$. However, the control gearing term was introduced to make the criterion applicable to vehicles exhibiting different dynamic response types. Therefore, for an Attitude Command Attitude Hold (ACAH) system the units of A_G will be deg/in and for a Translational Rate Command (TRC) system the units will be m/in.

From the input signal and output response, both the Phase Distortion Φ and the Aggression A_G parameters can be calculated. Both Φ and A_G can be computed with respect to time, allowing for observation of conditions where PIO incipience exists. However, each parameter calculation is related to a particular point in time, therefore each point can also be associated with the known frequency at that specific time. Hence, it is also possible to observe the PIO tendencies with respect to frequency other than with respect to time.

These two time-dependent, linked parameters can be plotted on a chart analogous to Gray's Duty Cycle - Aggression chart[20,21], but now called the Phase - Aggression chart. The PAC Chart represents a two-dimensional graph given by the results of the computation of the two parameters Φ and A_G.

Throughout a number of piloted simulation test campaigns (conducted in different closed-loop MTEs), it was possible to isolate regions characterizing the severity of PIO events, hence identifying 'No', 'Moderate' and 'Severe' regions of the chart in relation to the likelihood of PIO encounters. Different charts were produced, for different control axes (longitudinal and lateral), and for PIO Category I and II. Figure 4, for instance, represents the PAC chart for the longitudinal plane, both for Category I and Category II PIO type.

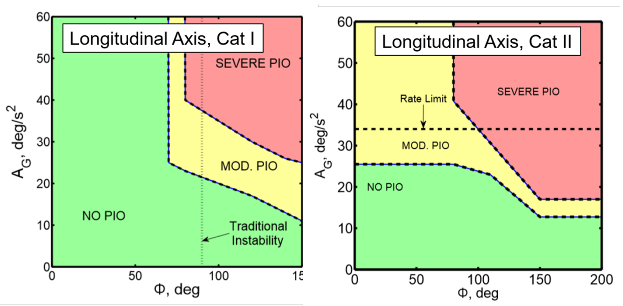

Figure 4: PAC Chart for the longitudinal plane, Category I and II PIOs

It can be easily noted that PIO situations occur when high A_G and high Φ are detected. A Phase Distortion of 90 deg between pilot input and vehicle output rate represents traditional instability, i.e. pilot input 180 deg out of phase with respect to the vehicle attitude output. Category I oscillations describe those cases where the PVS characteristics are essentially linear, i.e. situations where aircraft and pilot dynamics do not change during PIO events. Category II PIOs are characterized by a quasi-linear PVS with some non-linear contribution, such as rate or position limiters.

3.3. PAC Assessment as an in-Cockpit Warning System

One of the challenges that part of this work is meant to address is to understand whether a cockpit warning system, giving indications about the PIO incipience to the pilot, can be useful and based on the outcome of this aspect, to what extent automation can help the pilot in his/her task and reduce the workload. PAC was developed for Cat. I/II PIO detection off-line and now the idea is to assess it in real-time with an in-cockpit warning system. One of the devices that can be linked to the PAC and then implemented in an aircraft is a traffic light - style device, which can give indication of the severity of the PIO events, transitioning from green to amber, and from amber to red if the PVS is encountering, respectively, moderate or severe PIOs. After running a number of simulated flight trials with a test pilot inside the HeliFlight-R Motion Simulator at the University of Liverpool, he has been asked whether, during completion of a complex mission composed by different MTEs requiring high concentration and a certain amount of workload, the presence of a device detecting PIOs in real-time in the cockpit and alerting him about the presence and severity of a PIO event may be appreciated or not. Consequently, he was also asked whether he would rather prefer an automatic intervention. The answer was:

"*I have no issues with automation, I use automation a lot and we teach new pilots how to appropriately use automation. As a pilot what I don't want is a system that automatically prevents me from doing what I need to do in a specific moment. Therefore, a traffic light system showing when the boundaries to enter the moderate or severe PIO areas are crossed may be useful, but, if an automatic system had also to be present, I want to have the freedom to override the system and say "I am doing this, because I see with my eyes what is really going on". So, especially in manoeuvres where the pilot is required to perform high gains, isn't the automatic system impeding the pilot from doing what may be necessary to do? Wouldn't this be the equivalent of introducing a phase delay or a control limitation? So it is a tough question which I can't give you a straight answer to. Personally, I would like the system to tell me if there is a problem, but I want to take the decision, especially in critical situations. And if I am working really hard, then it comes down to what you are telling me and how you are going to tell me that I need to back off and do something different* "

Therefore, the point is that an automated system can be useful, but in a manoeuvre where high pilot control activity is required, the system may prevent the pilot from doing what he wants, impeding the pilot from achieving the goal of a mission. In the end the pilot would always want to be able to override and take control of the aircraft because he/she is the only one perceiving with his/her sensory system what is happening in reality. Hence, there must be a higher level mechanism evaluating whether the "system is wrong" and allowing the pilot to take control.

Another important aspect to consider is to understand, for Cat. I/II PIOs, to what extent the cockpit warning system can be useful in terms of pilot reaction time to the alert. In other words, the transition between green, amber and red will take a certain amount of time, what needs to be assessed is if this amount of time is sufficient or not to allow the pilot to react. Hence, the challenge will be to evaluate the compatibility of the cockpit warning system's transition time with the fact that an automatic takeover is undesirable when in difficult situations. If the transition time is too small for a human pilot to react then the issue is even more challenging and hard to solve.

3.4. Example of Characteristics for judging Cat. III PIO

There is no generalized effective criteria for detecting Cat. III PIO, thus one can qualitatively make an elementary judgment on whether the oscillation is a PIO from the following three characteristics of aircraft response states: amplitude (small, large), oscillation frequency (quick, slow), ultimate tendency (convergent, divergent). The combination used for judging is listed in Table 1.

The small amplitude and convergent tendency of the response state guarantees the safety of the aircraft. As for the oscillation frequency, it affects the pilot behavior, the higher the frequency, the harder it is for the pilot to take corrective actions to restore the aircraft from the PIO. For combination 1 and 2 in Table 1, the pilot may not need to do the corrective action, thus it can be regarded as no PIO although there are oscillations. For combination 3 and 4, the divergent tendency will make the aircraft unsafe but since the amplitude is small, if the oscillation frequency is slow, then it is possible for the pilot to do corrective action to recover from PIO, thus combination 3 can be regarded as moderate while combination 4 is moderate to severe. For combination 5 and 6, large amplitude during the flying task is a potential dangerous factor because the response of the aircraft may exceed its safe range. Even if the ultimate tendency is convergent it may also cause a moderate to severe PIO. The same analysis also applies to combination 7 and 8.

Table 1: Characteristics for judging PIO

Combination	Amplitude	Oscillation frequency	Ultimate tendency	Safety	PIO
1	Small	Quick	Convergent	Safe	No
2	Small	Slow	Convergent	Safe	No
3	Small	Slow	Divergent	Unsafe	Moderate
4	Small	Quick	Divergent	Unsafe	Moderate/Severe
5	Large	Quick	Convergent	Unsafe	Moderate/Severe
6	Large	Slow	Convergent	Unsafe	Moderate/Severe
7	Large	Slow	Divergent	Unsafe	Moderate/Severe
8	Large	Quick	Divergent	Unsafe	Severe

3.5. A Simple Analysis for understanding Cat III PIO – Build a simple simulation model

In order to get some physical feeling about Cat III PIO in helicopters, a simple model is used as example, i.e. a 3-DOF nonlinear longitudinal model involving surge, heave and pitch (u,w,q) as DOF. As the model is just related to longitudinal motion, the task in this paper is set to be a speed manoeuver: accelerating from hover to a constant speed, while keeping the altitude constant. The key response states of the helicopter are forward speed, pitch angle and altitude (V,θ,H). It is assumed that if the pitch angle exceeds its normal range, there is a potential for instability. Forward speed and altitude are used for judging the extent of completion of the task. As for the pilot model, according to McRuer[3], it is known that in analysing the PIO, the pilot model can be reduced to a simple gain, and considering the pilotâĂŹs operation delay, the pilot model in this paper is expressed as a simple gain with pure time delay: $K_p \cdot e^{-\tau_p}$

To this model a stability and command augmentation system (SCAS) model has been built for stabilization. The SCAS used in this paper is designed based on PID controllers. The pilot and SCAS inputs are added to generate the input to the actuator. In addition, the most significant nonlinearities in a given FCS mode are command gain shaping and rate limit and position saturation[12], thus the whole simulation model is built up as represented in Figure 5.

The percentage of the position of the cyclic and collective joystick to represent the pilot input is in the range [-50%, 50%]. The proposed command gain shaping of the pilot input is shown in Figure 6. Furthermore, it is assumed that the sensors are ideal, namely their transfer function is "1". The structure of the actuator dynamics is shown in Figure 7, where K is set as 20, and its reciprocal value represents the time constant of the actuator[23]. The input data of the 3-dof model represent the BO-105 helicopter, and the control range of its cyclic control and collective control being $\theta_c \in [-10, 5.5]$ deg and $\theta_0 \in [2, 18]$ deg respectively[24].

4. RESULTS

4.1. Simulation Performed

The top half of Figure 5 shows the vehicle triggers that may result in PIO. To study the influence of some of these vehicle triggers on PIOs, one first has to set a baseline scenario. The baseline scenario is an ideal case without actuator rate limit, no sensor dynamics, and also an ideal pilot model without time delay. Due to the safety and reliability problem of a full authority SCAS, in the baseline scenario, a partial authority SCAS is used to help control and stabilize the helicopter and the control authority is 30%. Then, the vehicle triggers are varied (e.g. time delay of helicopter main body, actuator rate limit, actuator position saturation, SCAS control authority) in order to see their influence in triggering PIO. The results of the baseline scenario (case 1) and other cases are listed in Table2.

Case 1, 2, 3 and case 5, 6, 7, 8 are performed for studying the influence of the pilot time delay in triggering PIO. Case 1, 4 and case 5, 9 are used for studying the influence of the helicopter time delay in triggering PIO. Cases 5, 10, 11, 12, 13 are implemented for studying the influence of the SCAS control authority on PIO triggering. Actually, the variation in SCAS control authority can be considered as an AFCS-induced saturation, which can also be regarded as a failure of SCAS. Case 14, 15, 16 is performed for researching the influence of actuator position saturation in triggering PIO. It can be regarded as a failure of actuator with the decrease of the manipulate range. Case 17, 18, 19, 20, 21, 22, 23 are cases related to the influence of actuator rate limit in triggering PIO. Reduction of actuator rate limit can be considered as a kind of actuator failure. Failures of SCAS and actuator are therefore transitions in effective controlled vehicle dynamics. Concluding, the PIOs induced in this paper are including decrease of control authority of SCAS, actuator position sat-

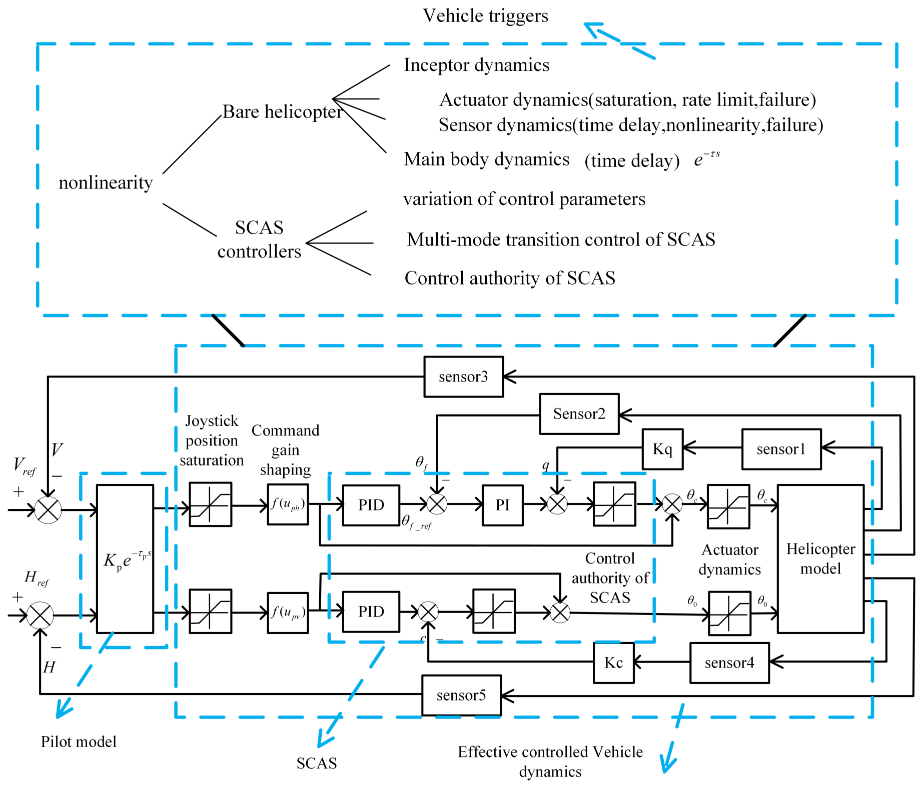

Figure 5: Simulation model with SCAS for BO 105

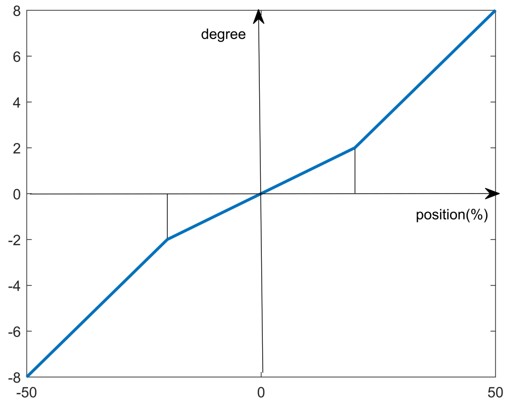

Figure 6: Command gain shaping of pilot input

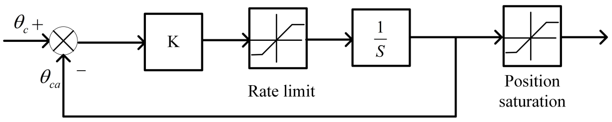

Figure 7: Actuator dynamics

Table 2: Speed maneuver results for BO105 accelerating from hover condition (0.1 m/s).

					Actuator saturation					
Case	SCAS limit	K_p	τ_p (s)	τ_b (s)	θ_c (deg)	θ_0 (deg)	Rate limit (deg/s)	Reference velocity (m/s)	Time domain results	PIO
1 Baseline?	30%	1	0	0	[-10, 5.5]	[2, 18]	no	0.1	No oscillation	No
2	30%	1	1.5	0	[-10, 5.5]	[2, 18]	no	0.1	Small slow convergent	No
3	30%	1	2	0	[-10, 5.5]	[2, 18]	no	0.1	Small slow divergent	Moderate
4	30%	1	0	0.1	[-10, 5.5]	[2, 18]	no	0.1	Small quick divergent	Moderate/Severe
5	30%	1	0	0	[-10, 5.5]	[2, 18]	no	10	No oscillation	No
6	30%	1	1.5	0	[-10, 5.5]	[2, 18]	no	10	No oscillation	No
7	30%	1	2	0	[-10, 5.5]	[2, 18]	no	10	Small slow divergent	Moderate
8	30%	3	0.5	0	[-10, 5.5]	[2, 18]	no	10	Large quick convergent	Moderate
9	30%	1	0	0.1	[-10, 5.5]	[2, 18]	no	10	No oscillation	No
10	15%	1	0	0	[-10, 5.5]	[2, 18]	no	10	No oscillation	No
11	10%	1	0	0	[-10, 5.5]	[2, 18]	no	10	Large quick convergent	Moderate/Severe
12	5%	1	0	0	[-10, 5.5]	[2, 18]	no	10	Large quick divergent	Severe
13	0%	1	0	0	[-10, 5.5]	[2, 18]	no	10	Large quick divergent	Severe
14	30%	1	0	0	[-10, 5.5]	[2, 18]	no	20	No oscillation	No
15	30%	1	0	0	[-6.15, 1.65]	[6, 14]	no	20	Small slow convergent	No
16	30%	1	0	0	[-4.25, -0.25]	[8, 12]	no	20	Large quick divergent	Severe
17	30%	1	0	0	[-10, 5.5]	[2, 18]	60	30	Small quick convergent	No
18	30%	1	0	0	[-10, 5.5]	[2, 18]	30	30	Small quick divergent	Moderate/Severe
19	30%	1	0	0	[-10, 5.5]	[2, 18]	10	30	Large quick divergent	Severe
20	30%	1/3	0	0	[-10, 5.5]	[2, 18]	10	30	Small quick convergent	No/Slight
21	30%	1	0	0	[-10, 5.5]	[2, 18]	10	20	No oscillation	No
22	30%	1/3	0	0	[-10, 5.5]	[2, 18]	2	30	Small quick convergent	No/Slight
23	30%	1	0	0	[-10, 5.5]	[2, 18]	2	10-20-30	Small quick convergent-no-no	No-No-No
24	30%	1	0	0	[-10, 5.5]	[2, 18]	no	20-30-40	No-No-Large quick divergent	No-No-Severe
25	100%	1	0	0	[-10, 5.5]	[2, 18]	no	20-30-40	No-No-No	No-No-No
26	30%	1/3	0	0	[-10, 5.5]	[2, 18]	no	20-30-40	No-No-No	No-No-No

uration and actuator rate limit, and therefore they belong to Cat. III PIO. Case 24 and 25 relate to the comparison between partial and full authority fly-by-wire flight control system.

4.2. Analysis of Results

Using Table1 to interpret the simulation results, the 25 above-given scenarios listed in Table2 result in following PIOs:

- The pilot vehicle system (PVS) is not very sensitive to time delay of the pilot, the SCAS helping to control and stabilize the helicopter and weakening the adverse effects of pilot time delay on the system. This conclusion is only true when assuming that there is no time delay introduced by the SCAS. Time delay introduced in the helicopter response has greater influence in triggering PIO than time delay of pilot does (case1 to case 4);
- Maintaining the hover condition is more difficult when introducing pilot or helicopter time delays and more prone to PIO and this depends on the velocity imposed in the speed maneuver (comparison between cases 2 to 4 and cases 6,7,9). This means that the effects of time delay are related to the performed flying task;
- With the increase in the pilot gain, the PVS will be PIO prone for a smaller time delay (case 6 and 8), which means that, if the time delay of the PVS is large, the pilot should manipulate more softly the controls in order to avoid PIO;
- With the decrease of the SCAS control authority, the PVS becomes increasingly prone to PIO (case 5, 10 to 13);
- Narrowing the control range of the actuator (the actuator being easier to saturate), the PVS becomes more PIO prone (case 14 to case 16);
- With the decrease of the rate limit value of the actuator, the PVS becomes increasingly prone to PIO (case 17 to case 19);
- Decreasing the pilot gain can help prevent the PVS from getting into PIO induced by the reduction of rate limit of the actuator (case 17, 18, 19, 20 and 22);
- Doing the velocity maneuver step by step (i.e. changing the reference velocity in steps) can

also help the PVS to not get into PIO (case 19 and 23);

- With the same saturation limit of the actuator position, SCAS with full authority can accomplish certain flying tasks free from PIO while the SCAS with partial authority result in triggering PIOs (case 24 and 25);
- Decreasing the pilot gain can contribute to preventing the PVS from falling into PIO triggered by the decrease of the control authority of the SCAS (case 24, 25 and 26).

Decreasing the pilot gain can be regarded as a transition of pilot control strategy. The flying tasks of Case 21 and 19 are different, and it can be viewed as a kind of task transition. From the results of cases 19, 20 and 21, one can conclude that the pilot control strategy should change in time while performing a task, otherwise there may be a mismatch between the pilot control strategy and the flying task. This kind of mismatch is a reason for triggering Cat. III PIO. The mismatch between transitions in effective controlled vehicle dynamics and pilot control strategy will result in Cat.III PIO, which is demonstrated by case 24, 25 and 26.

5. CONCLUSIONS

For modern aircraft equipped with a partial or total fly-by-wire flight control system, control authority of the SCAS is an important factor in triggering Cat. III PIO. This is due to the fact that variation of control authority can be regarded as a kind of transition of effective controlled vehicle dynamics. Although PIO caused by actuator position saturation and actuator rate limit are usually classified as Cat. II PIO, one can also consider PIO caused by these two factors as Cat. III as the variation of actuator position saturation and actuator rate limit can be considered as well as a transition of effective controlled vehicle dynamics . These factors belong to a mismatch between transitions in effective controlled vehicle dynamics and pilot control strategy. Furthermore, PIO is related to task transitions, and a mismatch between the pilot control strategy and the flying task can lead to Cat. III PIO.

5.1 Way Forward

In this paper, some factors triggering Cat. III PIO were analysed. The analysis shown in this paper is simple but can help to a fundamental understanding of Cat. III PIO definition. In the future the analysis will be extended to include more factors that may lead to Cat. III PIO, such as sensor dynamics, inceptor dynamics and multi-mode transitions of flight control system. For multi-mode transitions of flight control system in triggering Cat. III PIO, different control modes will be designed in the flight control system (FCS) (e.g. RCAH, ACAH, TRC, PH) meeting the ADS-33 specification basic FCS modes description[5]. The pilot will control the vehicle manually based on these response types in order to accomplish a designed flying task with multi-mode transitions switched on automatically during the flight. Then, a more robust SCAS system will be also designed based on advanced control theory (e.g. NDI, INDI method[25,26]), the goal being to study its function in preventing PIO. Last but not the least, extending and improving existing criteria for predicting Cat. III PIO is urgent as well since at the present little criteria can be used for detection and prediction of Cat. III PIO.

6. FUTURE PLANNING

6.1. Pilot Identification

Aside from PAC development it would be of particular importance to implement, within the NITROS project and specifically in the research related to RPCs, some relevant flight simulation aspects, such as pilot identification and cybernetic techniques to study pilotâĂŹs control behaviour with control parameters estimation, similarly to some other work previously undertaken at the University of Liverpool and Delft University of Technology[19,27,28], relating the Phase Aggression Criterion to Pilot Identification during Rotorcraft Pilot Couplings.
Regarding pilot control behaviour study, it may be interesting to understand how and when the pilot is changing control strategy and control behaviour. Objective measurements of pilot changing behaviour and adaptation[29,30], through pilot identification techniques, can be useful to understand when the pilot is going to induce PIO events and potentially anticipate his/her triggering action.

6.2. Scalograms

Another avenue where PIO events may be investigated may be undertaken with the use of wavelet scalogram-based metrics[31]. These metrics consider the time-varying peak pilot input power as a function of the controlled element phase at the frequency of the peak power, all of which are indicators of the PIO signature defined by Mitchell[22]. In Klyde's view, "Wavelet transform is a way to characterize time-varying systems, this is a powerful tool for detecting changes in more transient or time varying pilot-vehicle systems including PIO scenarios, because the wavelet scalogram shows both the peaks in power and when in time the sinusoid occurred"[31]. Moreover, according to Masarati, "Typical PIOs are intrinsically time dependent and characterized by intrinsic frequency aspects, therefore methods capable of simultaneously capturing frequency and time domain related aspects are desirable"[32], and again "Wavelet transforms play an important role in the analysis of signals whose frequency content is significantly time-dependent and it is thought that such approach can provide a formulation of indicators associated with the insurgence of adverse RPC events". The work performed in[32] made use of the ROVER and PAC methods within a sound time-frequency approach, in order to exploit their capability to link the energy in signals to both its frequency content and its position in time, in an attempt to identify those changes that may reveal the action of a trigger. Further research is needed to meet this goal.

6.3. Cockpit Warning System

Going forward with the research, as already mentioned in the previous chapters, the next step will be to improve the capabilities of PAC during detection of PIO events either before or as they are occurring, with a cockpit warning system to provide the pilot with useful cueing of what is happening and developing means of alleviating adverse RPC. To design the alert system the PAC chart boundaries can be used. Different ideas may be employed for the warning system, such as:

- Traffic light - style device: green, amber, red flashing lights associated with the three regions of PIO severity. Green means "no PIO", amber means "moderate PIO", red means "severe PIO",
- Haptic device on the active inceptor system alerting the pilot that some kind of instability is occurring. The aim is to lead the pilot to reduce the aggression by means of a change in stick force through a haptic device
- Sound: a noise of a certain intensity when crossing the boundary of moderate/severe PIO events
- Display design. A polygon indicating the relevant parameters along with their thresholds (for PIO incipience), similarly to the ROVER flags, directly showing to the pilot in quantitative terms the incipience of PIO events.

REFERENCES

[1] M. D. Pavel, M. Jump, B. Dang-Vu, P. Masarati, M. Gennaretti, A. Ionita, L. Zaichik, H. Smaili, G. Quaranta, D. Yilmaz, M. Jones, J. Serafini, and J. Malecki. Adverse Rotorcraft-Pilot Couplings - Past, Present and Future Challenges. *Progress in Aerospace Sciences*, 62:1–51, 2013.

[2] McRuer D. T. Pilot-Induced Oscillations and Human Dynamic Behavior. *Tech. Rep. NASA Contractor Report 4683, NASA*, 1995.

[3] McRuer D. T. Aviation Safety and Pilot Control: Understanding and Preventing Unfavorable Pilot-Vehicle Interactions. *National Academy Press, Washington D.C. Committee on the Effects of Aircraft-Pilot Coupling on Flight Safety Aeronautics and Space Engineering Board Commission on Engineering and Technical Systems National Research Council.*, 1997.

[4] Padfield G. D. Helicopter Flight Dynamics: The Theory and Application of Flying Qualities and Simulation Modelling. *Blackwell Publishing, Oxford, United Kingdom, 2nd ed.*, 2007.

[5] Anon. Aeronautical Design Standard Performance Specification Handling Qualities Requirements for Military Rotorcraft. *Tech. Rep. ADS-33E-PRF, United States Army Aviation and Missile Command Aviation Engineering Directorate*, 2000.

[6] M. D. Pavel, P. Masarati, M. Gennaretti, M. Jump, L. Zaichik, B. Dang-Vu, L. Lu, D. Yilmaz, G. Quaranta, A. Ionita, and J. Serafini. Practices to Identify and Preclude Adverse Aircraft-and-Rotorcraft-Pilot Couplings -âĂŞ a design perspective. *Progress in Aerospace Science*, 76:55–89, 2015.

[7] Jones M. and Jump M. New Methods to Subjectively and Objectively Evaluate Adverse Pilot Couplings. *Journal of the American Helicopter Society*, 60:011003–1 – 011003–13, 2015.

[8] Liu J. Q. and Gao Z. H. The Prediction of PIO Susceptibility of a Large Transport Aircraft. *IEEE, International Conference on Signal Processing Systems (ICSPS)*, pages 472–477 Vol.3, 2010. doi:10.1109/ICSPS.2010.5555735.

[9] Jones M., Jump M., and Lu L. Development of the Phase-Aggression Criterion for Roforcraft-Pilot Coupling Detection. *AIAA Journal of Guidance, Control and Dynamics*, 36(1):35 – 47, January-February 2013. doi:10.2514/1.58232.

[10] Jones M. and Jump M. Prediction of Rotorcraft Pilot-Induced Oscillations using the Phase-Aggression Criterion. *AHS 69th Annual Forum*, 21–23 May 2013.

[11] Jones M. and Jump M. Subjective and Objective Evaluation of PIO Tendencies. *AHS 70th Annual Forum*, 20–22 May 2014.

[12] McRuer D. T., Klyde D. H., and Myers T. T. Development of a Comprehensive PIO Theory. In *AIAA Atmospheric Flight Mechanics Conference*, San Diego, CA, USA, July 29–31 1996. AIAA-1996-3433.

[13] Klyde D. H., McRuer D. T., and Myers T. T. Unified Pilot-Induced Oscillation Theory, Volume 1. PIO Analysis with Linear and Nonlinear Effective Vehicle Characteristics, including Rate Limiting. TR 96-3028, FDDWL, December 1995.

[14] Bauer C. J. A Landing and Takeoff Control Law for Unique-Trim, fly-by-wire Rotorcraft Flight Control Systems. In *19th European Rotorcraft Forum*, pages H10–1–9, Como, Italy, September 14-16 1993.

[15] Stiles L. R., Mayo J., Freisner A. L., Landis K. H., and Kothmann B. D. “Impossible to Resist” the Development of Rotorcraft fly-by-wire Technology. In *60th Annual Forum*, Baltimore, MD, June 8-10 2004.

[16] Walden R. B. A Retrospective Survey of Pilot-Structural Coupling Instabilities in Naval Rotorcraft. In *63rd Annual Forum*, pages 1783–1800, Virginia Beach, VA, May 1–3 2007.

[17] Tischler M. B. System Identification Requirements for High-Bandwidth Rotorcraft Flight Control System Design. 13(5):835–841, 1990. doi:10.2514/3.25409.

[18] Ockier C. J. Pilot Induced Oscillations in Helicopters – Three case studies. Technical Report IB 111-96/12, German Aerospace Center (DLR), Braunschweig, Germany, 1996.

[19] Jones M., Jump M., Lu L., Yilmaz D., and Pavel M. D. Using the Phase-Aggression Criterion to Identify Rotorcraft Pilot Coupling Events. *38th European Rotorcraft Forum, Amsterdam, The Netherlands, September 4âĂŞ7*, 2012.

[20] Gray W. R. Boundary-Avoidance Tracking: A new Pilot Tracking Model. *AIAA Atmospheric Flight Mechanics Conference*, pages 86–97, 15-18 August 2005. USAF Test Pilot School, Edwards AFB, CA 93524, San Francisco, CA.

[21] Gray W. R. Handling Qualities Evaluation at the USAF Test Pilot School. *AIAA Atmospheric Flight Mechanics Conference*, 10-13 August 2009. Chicago, Illinois.

[22] Mitchell D. G. and Klyde D. H. Identifying a PIO Signature – New Techniques applied to an old Problem. *AIAA 2006 Atmospheric Flight Mechanics Conference, Keystone (CO)*, 2:992–1006, Aug. 2006.

[23] Yildiz Y. and Kolmanovsky I. V. A Control Allocation Technique to Recover from Pilot-Induced Oscillations (CAPIO) due to Actuator Limiting. *IEEE American Control Conference*, pages 516–523, 2010. doi:10.1109/ACC.2010.5530869.

[24] van Hoydonck W. R. M. and Pavel M. D. Investigation on the Simulation and Handling Qualities for Helicopters Operating near Ship Decks. *AIAA Modeling and Simulation Technologies Conference, Denver, Colorado*, 2006.

[25] Simplicio P., Pavel M. D., van Kampen E., and Chu Q.P. An Acceleration Measurements-based Approach for Helicopter Nonlinear Flight Control using Incremental Nonlinear Dynamic Inversion. *Control Engineering Practice*, 2013. 21(8), 1065-1077.

[26] Pavel M. D., Shanthakumaran P., Stroosma O., Chu Q., Wolfe M., and Cazemier H. Development of Advanced Flight Control Laws for the AH-64 Apache Helicopter - Sketches from the work of TU Delft-Boeing project in SIMONA simulator. *Proceedings of the AHS 72nd Annual Forum, West Palm Beach, Florida, USA, May 17-10*, 2016.

[27] Yilmaz D., Pavel M. D., Jones M., Jump M., and Lu L. Identification of Pilot Control Behavior during possible Rotorcraft Pilot Coupling Events. *38th European Rotorcraft Forum, Amsterdam, The Netherlands, September 4âĂŞ7*, 2012.

[28] Lu T., Pool D. M., van Paassen M. M., and Mulder M. Quantifying the Effects of Added Dynamics with Human Operator Control Behavior Measurements and Simulations. *Proceedings of the AIAA Modeling and Simulation Technologies Conference, Denver(CO)*, 2017. doi:10.2514/6.2017-3667.

[29] McRuer D. T., Graham D., Krendel E. S., and Reisener W. Jr. Human Pilot Dynamics in Compensatory Systems, Theory Models and Experiments with Controlled Element and Forcing Function Variations. Technical Report AFFDL-TR-65-15, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base (OH), 1965.

[30] McRuer D. T. and Jex H. R. A Review of Quasi-Linear Pilot Models. *IEEE Transactions on Human Factors in Electronics*, HFE-8(3):231–249, September 1967.

[31] Klyde D. H. Assessment of a Scalogram-based PIO Metric with Flight Test Data. *AIAA 2017 Atmospheric Flight Mechanics Conference*, 2017.

[32] P. Masarati, D. Franzoni, and G. Guglieri. A Time-Frequency Domain Approach for PIO/PAO Detection and Analysis. In *AHS 72nd Annual Forum*, West Palm Beach, FL, USA, May 17–19 2016.