Adverse Rotorcraft-Pilot Couplings - Prediction and Suppression of Rigid Body RPC *Sketches from the Work of Garteur HC-AG16*

Marilena D. Pavel
Delft University of Technology
Kluyverweg 1
NL-2629 HS Delft
The Netherlands
Tel.: +31 15 278 39 92
Fax.: +31 15 278 34 44
m.d.pavel@tudelft.nl

Binh Dang Vu
ONERA
Base Aerienne 701
FR-13661 Salon de Provence
France
Tel.: +33 4 90 17 01 02
Fax.: +33 4 90 17 01 09
binh.dangvu@onera.fr

Joachim Götz
DLR
Lilienthalplatz 7
D-38106 Braunschweig
Germany
Tel.: +49 531 295 3259
Fax.: +49 531 295 2641
joachim.goetz@dlr.de

Michael Jump
University of Liverpool
Room 2.05 Chadwick Tower Peach Street
Liverpool L69 7ZF
UK
Tel.: +44 151 794 6845
Fax.: +44 151 794 6841
mjump1@liverpool.ac.uk

Oliver Dieterich
Eurocopter Deutschland GmbH
Postbox
D-81663 Muenchen
Germany
Tel. +49 89 6000 4637
Fax. +49 89 6000 6888
oliver.dieterich@eurocopter.com

Keywords: Pilot Induced Oscillations (PIO), Rigid Body Rotorcraft-Pilot Coupling (RPC), Flight control system (FCS)

Abstract: Rotorcraft-pilot-couplings (RPCs) of today helicopters seem to be highly more problematic for safety than aircraft-pilot couplings (APCs). GARTEUR organisation (Group for Aeronautical Research and Technology in Europe) has recently engaged the industry, research laboratories and academia in the group GARTEUR HC-AG16 with the goal of assessing the problems associated with undesirable RPCs. The goal of the present paper is to give an overview of the GARTEUR work performed on rigid body RPC. Rigid body RPC involve adverse coupling phenomena dominated by helicopter lower frequency dynamics (range at frequencies of approximately 1 Hz and below) characteristic to flight mechanics modeling and an active pilot "keen" to fulfil the mission task by actively controlling the rotorcraft. Using a state-space identified model enhanced by a full authority fly-by-wire RCAH-type flight control system, the paper will demonstrate that: 1) the bandwidth/phase delay criterion and Gibson average phase rate criterion used for Cat. I PIO prediction of fixed wing aircraft can be applied also for helicopters. Low dynamics and high time delays result in general in a PIO prone system. 2) the OLOP criterion used for Cat. II PIO analysis shows that the boundaries for helicopters lie between the fixed wing aircraft original OLOP boundary and the modified OLOP2 boundary. The paper investigates the concept of "boundary avoidance" for RPC analysis. In this respect, it will be shown that the condition for a RPC onset depends on the value of the minimum time to boundary which has to be proportional to the system time delay. The closer are the boundaries, the higher the tendency to develop RPC.

Nomenclature

A = system matrix (-)
B = control matrix (-)
C = FCS system matrix (-)
f = vector of non-linear functions (-)
$\underline{x}$ = state vector (-)
$\underline{u}$ = pilot control vector (-)
$\underline{y}$ = FCS state vector (-)
u_{FBK} = Feedback control vector (-)
u_{FCS} = FCS control vector [-]
K_{ffw} = FCS feedforward gain matrix [-]
K_{fbk} = FCS feedback gain matrix [-]
p = roll rate [rad/s]
q = pitch rate [rad/s]
r = yaw rate [rad/s]
$t_{\min}$ = minimum time to boundary in the BAT concept [s]
u, v, w = velocity components [m/s]
g = gravity [m/s^2]
$I_{xx}, I_{yy}, I_{zz}, I_{xz}$ = moments of inertia [kgm^2]
δ = system time delay (msec)
δ_0 = collective pilot control [%]
δ_p = pedal pilot control [%]
δ_x = longitudinal pilot control [%]
δ_y = lateral pilot control [%]
ϕ = roll angle [rad]
θ = pitch angle [rad]
ψ = yaw angle [rad]

1. INTRODUCTION and BACKGROUND

Pilot induced oscillations (PIOs) have plagued piloted aircraft and rotorcraft since the beginnings of powered flight. Generally they are defined as "*inadvertent, sustained aircraft oscillations as a consequence of an abnormal joint enterprise between the aircraft and the pilot*" [ref. 1]. In other words, PIOs are sustained or uncontrollable oscillations resulting from the efforts of the pilot to control the aircraft. These undesirable oscillations may result in potential instabilities and limit cycle oscillations, degrading aircraft handling qualities and exceeding the vehicle structural strength limits. While the PIOs of early aircraft were due almost entirely to the pilot or to poor design, today's PIOs are far more complex and varied from those encountered in the past. Recently a new term for PIO has been introduced: aircraft/rotorcraft-pilot coupling (APC/RPC). Reference 2 underlines that it is important to note that the new correct term is unfavorable APC/RPC, since it can be argued that normal pilot control is favorable APC/RPC. The term APC/RPC will be used throughout the present paper.

As regarding the rotorcraft-pilot coupling (RPC), rotorcraft design tends to lag aircraft design by some two decades. Table 1 summarizes a short collection of famous adverse RPCs occurring during the years.

Type	Year	Associated with	Ref
BO 46	1964	Rotor Control/gyro system coupling	23
CH-47	1968	Rotor/Sling Load Bounce	24
AH-56	1970	Flexible Control Actuation System	25
CH-53E (USN)	1978	Flexible Mode-Sling Load Interaction	26,33
CH-53 G (GAF)	1980	Flexible Mode-Sling Load Interaction	27
UH-60 ADOCS	1988	Excessive time delays	28
V-22	1989	Flight Control/ Flexible Mode Interaction	29, 33
BO 105 ATTHeS	1993	Time delay/attitude command	30
BO 105 ATTHeS	1995	Biomechanical/Airframe coupling	31
EC 135	2008	Air resonance controller introduced in the FCS system	32
EC 145	-	FCS system	
Tiger	-	FCS system	

Table 1: Adverse Rotorcraft-Pilot Coupling Occurrences [ref. 3 + new occurrences]

Recent experiences showed that research helicopters that incorporated advanced FCS systems exhibited RPCs in several high gain tasks including landing, tracking tasks or other aggressive manoeuvres. RPCs of today's helicopters seem to be highly more problematic for safety than APCs. The reason for this is that, in general, rotorcraft, in particular military helicopters, have to be capable of precise and aggressive manoeuvring close to he ground at night and in bad weather. Therefore, rotorcraft handling qualities are specifically tailored to the demands of different manoeuvres by using complex flight control systems (FCS). The problem is that each FCS component of an actively controlled rotorcraft introduced to improve handling qualities adds extra high-order dynamics to the rotorcraft-pilot system. The bare rotorcraft dynamics will couple to the pilot and FCS dynamics, changing the final rotorcraft behaviour. Figure 1 from ref. 3 shows the multitude of integrated FCS components that can be used to improve handling qualities. One can see different components as inceptors (manipulators) and effectors (actuators and rotor blade controllers), sensors, display and software interfaces (control and display laws). Hence, different flight control laws can be programmed for different flight phases, for example attitude command attitude hold (ACAH) for precision landing or slalom manoeuvre, rate command attitude hold (RCAH) for nap-of-the-earth flight, etc. "*The higher-order dynamics of actively controlled rotorcraft will result in reduced system bandwidth and increased system phase delay which is directly related to the total effective time delay of the rotorcraft-pilot system...Effective time delays of more than 200 ms (50-70ms inherent rotor response delay, 30ms actuator delay and additional delays due to digital computing, sensor signal shaping and filtering) may reveal poor handling qualities due to high-gain tasks. They exhibit potential sources of adverse rotorcraft-pilot coupling.*"[ref. 3]

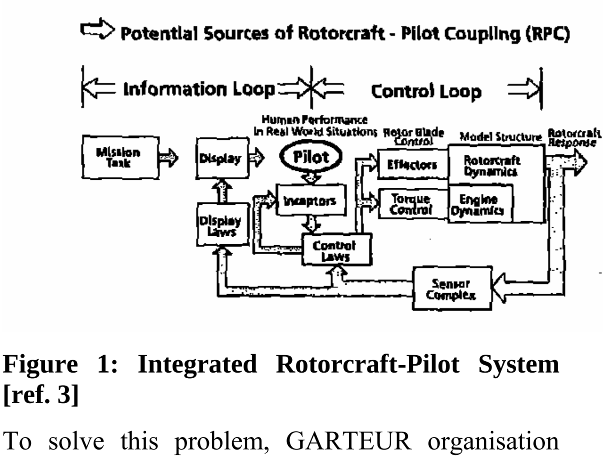


Figure 1: Integrated Rotorcraft-Pilot System [ref. 3]

To solve this problem, GARTEUR organisation (Group for Aeronautical Research and Technology in Europe) has recently engaged the industry, research laboratories and academia in the group GARTEUR HC-AG16 with the goal of assessing the problems associated with undesirable RPCs and to recommend technologies for prediction and suppression of these oscillations [refs. 4, 5, 6]. The group has divided the RPC phenomena into two categories: 1) lower frequency range RPC at frequencies of approximately 1 Hz and below or "*rigid-body RPC*" involving adverse coupling phenomena dominated by helicopter low frequency dynamics i.e. flight mechanics characteristics, by the flight control system and by an active pilot "keen" to fulfil the mission task by actively controlling the rotorcraft; 2) high frequency range RPC at frequencies of 2 Hz up to 8 Hz or "*aeroelastic RPC*" corresponding to higher frequency dynamics, i.e. elastic airframe and main rotor blades modes, which involve more a passive pilot subjected to vibrations. The goal of the present paper is to give an overview of the GARTEUR work performed on *rigid body RPC*. As helicopter example, the paper will concentrate on a BO105 model and on two flight conditions, i.e. hover and 65 kts straight flight.

2. HELICOPTER-PILOT MODELLING FOR RIGID BODY RPC

A simplified rotorcraft model was employed in the study of the RPC proneness named BO105 "Baseline model". It is an identified state space model provided by DLR [ref. 7] and features 8 degrees of freedom corresponding to a rigid airframe, a rigid main rotor with equivalent hinges and a teetering rigid tail rotor. The vehicle dynamics are:

$$\begin{aligned}
\dot{\underline{x}} &= A\underline{x} + f + B\underline{u} \\
\dot{\phi} &= p + (q\sin\phi + r\cos\phi)\tan\theta \\
\dot{\theta} &= q\cos\phi - r\sin\phi \\
\dot{\psi} &= (q\sin\phi + r\cos\phi)/\cos\theta
\end{aligned} \qquad (1)$$

with
$\underline{x} = \begin{pmatrix} u-u_{trim} & v-v_{trim} & w-w_{trim} & p & q & r & \dot{p} & \dot{q} \end{pmatrix}^T$
the state vector corresponding to helicopter translational and rotational velocities in x-,y- and z-axis and φ,θ,ψ the Euler angles; $\underline{u} = \begin{pmatrix} \delta_x - \delta_{xtrim} & \delta_y - \delta_{ytrim} & \delta_0 - \delta_{0trim} & \delta_p - \delta_{ptrim} \end{pmatrix}^T$ the control vector corresponding respectively to longitudinal, lateral, collective and pedal pilot controls; A and B the matrices of state derivatives and control derivatives and f the nonlinear contribution due to gravity, inertial couplings and flight dynamics couplings. One can see that the DLR identified model is characterized by an extension of the differential equation in roll and pitch to equations of second order, these additional degrees of freedom being substituted to the longitudinal and lateral flapping. The non-linear term f is given by:

$$f = \begin{bmatrix}
-q(w-w_{trim}) + r(v-v_{trim}) - g(\sin\theta - \sin\theta_{trim}) \\
-r(u-u_{trim}) + p(w-w_{trim}) + g(\cos\theta\sin\phi - \cos\theta_{trim}\sin\phi_{trim}) \\
q(u-u_{trim}) - p(v-v_{trim}) + g(\cos\theta\cos\phi - \cos\theta_{trim}\cos\phi_{trim}) \\
\dfrac{1}{1-I_{xz}^2/I_{xx}I_{zz}}\left[\left(\dfrac{I_{yy}-I_{zz}}{I_{xx}} - \dfrac{I_{xz}^2}{I_{xx}I_{zz}}\right)qr + \dfrac{I_{xz}}{I_{xx}}\left(1+\dfrac{I_{xx}-I_{yy}}{I_{zz}}\right)pq\right] \\
\dfrac{I_{zz}-I_{xx}}{I_{yy}}pr - \dfrac{I_{xz}}{I_{yy}}(p^2-r^2) \\
\dfrac{1}{1-I_{xz}^2/I_{xx}I_{zz}}\left[\left(\dfrac{I_{xx}-I_{yy}}{I_{zz}} + \dfrac{I_{xz}^2}{I_{xx}I_{zz}}\right)pq + \dfrac{I_{xz}}{I_{zz}}\left(-1+\dfrac{I_{yy}-I_{zz}}{I_{xx}}\right)qr\right] \\
0 \\
0
\end{bmatrix} \qquad (2)$$

The state trim values $(u_{trim} \quad v_{trim} \quad w_{trim} \quad \phi_{trim} \quad \theta_{trim})$ and the control trim values $(\delta_{xtrim} \quad \delta_{ytrim} \quad \delta_{0trim} \quad \delta_{ptrim})$ together with the system matrix A and control matrix B have been provided by DLR and correspond to two flight conditions: hover and level flight 65kts (i.e. 120 km/h or 33m/s). The signs of the pilot controls are specified in ref. 7 as: Longitudinal control δ_x: -100% pushed and +100% pulled; Lateral control δ_y -100% left,+100% right; Collective control δ_0: 0% pushed down, +100% pulled up; Pedal control δ_p: -100% pushed left, +100% pushed right. Each partner of the GARTEUR group had also their "in-house" theoretical models for helicopter modeling (example TUD had an 8 dof model body-first order flapping dynamics $(u, v, w, p, q, r, \beta_{1c}, \beta_{1s})$, DLR and ONERA a 10th order HOST [ref. 8] model body-second order flapping dynamics $(u, v, w, p, q, r, \beta_{1c}, \beta_{1s}, \dot{\beta}_{1c}, \dot{\beta}_{1s})$, Univ. of Liverpool and NLR a FLIGHTLAB model [ref. 9]. All the partners tried to adjust their model as good as possible to the identified baseline model and used it as a reference. Figure 2 presents for example the pole map of the HOST model as compared to the identified baseline modes of eq. (1).

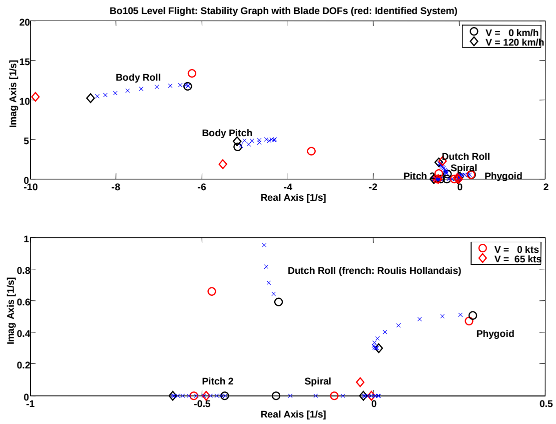


Figure 2: Eigenvalues of the BO105

One can see that the theoretical and identified eigenvalues of the Dutch roll for hovering case are quite different in damping. Responses to a (3-2-1-1) pedal input were also compared on Figure 3 for the baseline model and the identified state-space model (SSM) together with flight tests data. One can see a good agreement between the short term response of the baseline model and the flight tests.

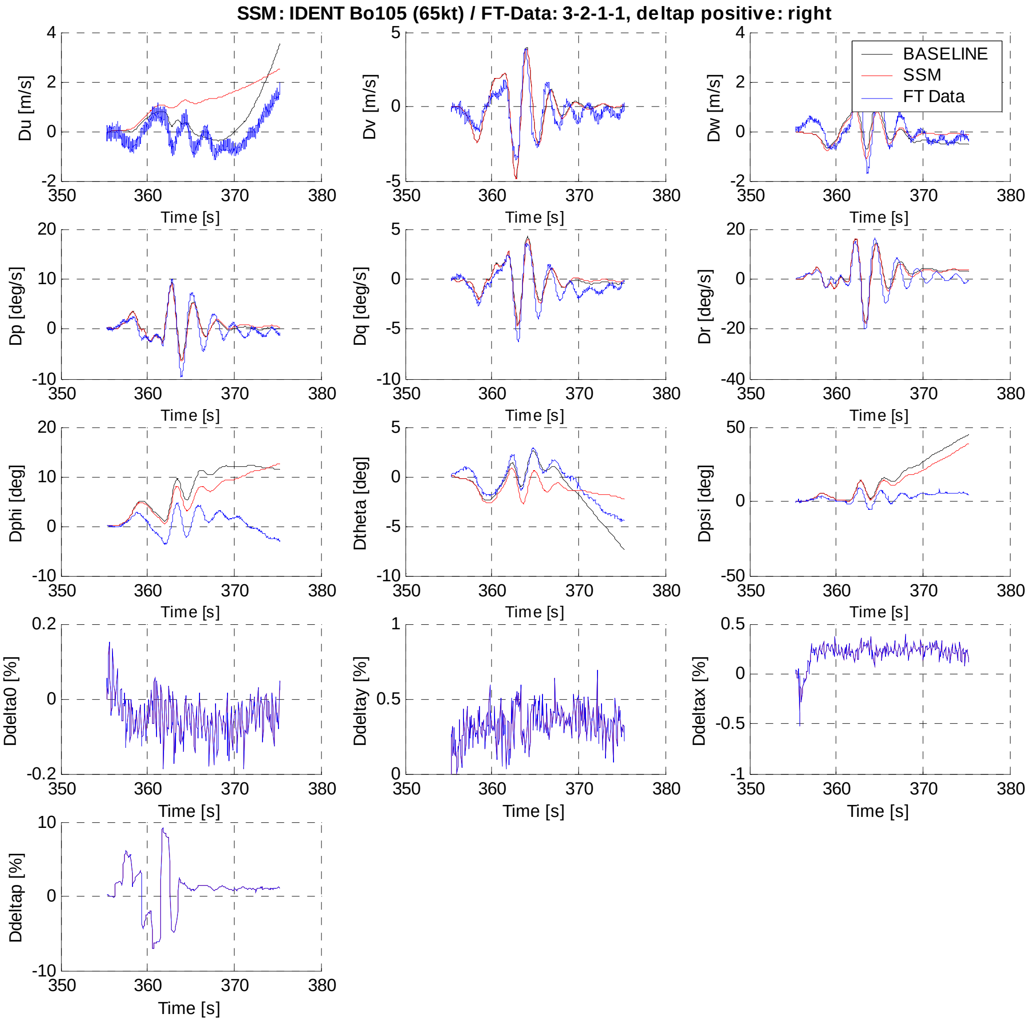


Figure 3 Comparison between the baseline model, the SSM model and the flight test data

For RPC analysis, the state space model (1) has been linearized. The linear model is represented by the equivalent system:

$$\dot{\underline{x}} = (A + f')\underline{x} + B\underline{u} \qquad (3)$$

where f' contains the derivatives $\partial f / \partial x = (f - f_{trim}) / \Delta x$ of the nonlinear term f. By definition of the non-linear term *f*, $\partial f / \partial x = (f - f_{trim}) / \Delta x$ is equal to zero at trim conditions. The linear model is then simply:

$$\dot{\underline{x}} = A\underline{x} + B\underline{u} \qquad (4)$$

This was done because RPC analysis involves usually criteria which are mode based (this has historical reasons as early PIOs were mainly due to deficiency in short period damping or low control sensitivity and therefore needed criteria predicting these specific modes).

Next, the non-linear state space model of the BO105 helicopter was augmented with a full-authority flight control system (FCS). This was done in order to present a large bandwidth characteristic for RPC prediction. Figure 4 presents the BO105 with generic augmented dynamics analysis. One can see that the pilot inputs, together with the FCS system, provide the input to the rotorcraft model, the rotorcraft states being fed back to the FCS system.

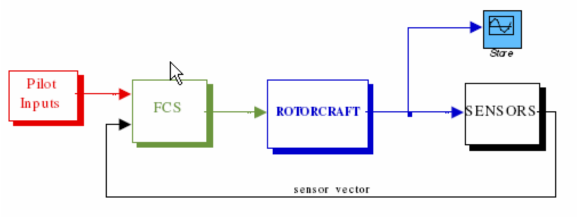


Figure 4: Generic modelling of the helicopter-FCS system

For the FCS system, a full-authority fly-by-wire RCAH-type control law was added to the original model (see Figure 5). This gives what is called the "Augmented BO105 model". The function of the longitudinal controller is pitch rate control with attitude hold. The lateral and directional controller enables the pilot to perform roll rate and yaw rate control with attitude hold. The function of the vertical controller is vertical speed control in body-axes. The designed FCS has tunable feed-forward and feedback gains to provide the vehicle with varying flying qualities which comply with the ADS-33 requirements from Level 1 to Level 3. In addition, the ability to introduce time delays to the model control circuit was provided to create vehicles of different RPC proneness.

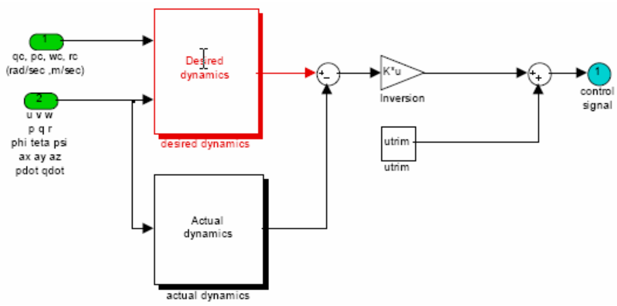


Figure 5 Diagram of the FCS system

The dynamics of the augmented helicopter model is given by:

$$\begin{bmatrix}\dot{\underline{x}}\\ \dot{\underline{y}}\end{bmatrix}=\begin{bmatrix}A & 0\\ C & 0\end{bmatrix}\begin{bmatrix}\underline{x}\\ \underline{y}\end{bmatrix}+\begin{bmatrix}f\\ 0\end{bmatrix}+\begin{bmatrix}B\\ 0\end{bmatrix}u_{FBK}+\begin{bmatrix}K_{xffw}\\ K_{yffw}\end{bmatrix}\underline{u}$$

$$\dot{\phi}=p+\left(q\sin\phi+r\cos\phi\right)\tan\theta \quad (5)$$

$$\dot{\theta}=q\cos\phi-r\sin\phi$$

$$\dot{\psi}=\left(q\sin\phi+r\cos\phi\right)/\cos\theta$$

where

$\underline{x}=\left(u-u_{trim}\quad v-v_{trim}\quad w-w_{trim}\quad p\quad q\quad r\quad \dot{p}\quad \dot{q}\right)^T$ is the helicopter state vector; $\underline{u}=\left(\delta_x-\delta_{xtrim}\quad \delta_y-\delta_{ytrim}\quad \delta_0-\delta_{0trim}\quad \delta_p-\delta_{ptrim}\right)^T$ is the pilot control input vector; $\underline{y}=\left(y_1\quad y_2\quad y_3\quad y_4\right)^T$ is the flight control system state vector. The feedback control law is given by:

$$u_{FBK}=\begin{bmatrix}K_{xfbk} & K_{yfbk}\end{bmatrix}\begin{bmatrix}\underline{x}\\ \underline{y}\end{bmatrix} \quad (6)$$

The gain matrices K_{xffw}, K_{yffw} and K_{xfbk}, K_{yfbk} are obtained analytically by shaping the pitch, roll, heave and yaw responses to the desired dynamics.

Commenting on the adequacy of the mathematical model considered in this paper, the GARTEUR group considered that by using a state space model augmented with a numerical FCS, the dynamic behaviour of the BO105 could easily be modified for RPC analysis. The level of fidelity considered in the state space model can approximate the helicopter behaviour in the range of modeling for pilot compensatory behavior, i.e. up to 0.8 Hz. Therefore, the model used is able to reveal the RPCs in the range of 1-5 rad/sec (0.16-0.8 Hz) that are associated with pilot behavior in the compensatory loop and corresponds to rigid body RPC prediction.

The GARTEUR HC-AG16 group undertook two different approaches to model the pilot for RPC analysis. From the beginning it was decided that the pilot model to be designed had to explicitly concentrate on the pilot effort in the compensatory loop. This means that the pilot exerts continuous closed-loop control on the aircraft in order to minimize the error existing between the commanded signal and the helicopter response. The pilot model fulfils the function of guidance and stabilization. The guidance function is achieved by means of the FCS system as described above. For the stabilization function, two approaches have been used: 1) one model is based on the principles of crossover modeling [ref. 1]; 2) the other model is based on a new approach currently under development at TUD, the so-called boundary-avoidance tracking. The latter will be extensively treated in section 4 of this paper.

Figure 6 presents the basic principles for the compensatory control in the crossover model for the roll axis. The incoming signal (for example the desired roll attitude ϕ_{des}) is captured from the guidance level and is processed by the pilot at the stabilization level. To initiate the PIO, a variable time delay of 0, 100 and 200 msec has been introduced in the pilot control (time delay in processing the visual, proprioceptive or vestibular signals). The pilot output then enters the FCS system and the rotorcraft model resulting in changes to the helicopter states (i.e. roll attitude ϕ). The helicopter states are fed-back in a closed-loop to the pilot, the pilot applying the input based on the error needed to change the attitude from ϕ to ϕ_{des}. The essence of the cross-over model is that increasing pilot gain, K_p, leads to instability.

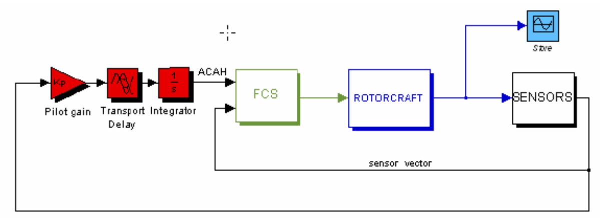


Figure 6 Compensatory control behavior in the cross over pilot model

3. RPC PREDICTION

Up to the present, the criteria employed in the prediction of contemporary rotorcraft RPCs have been largely drawn from fixed-wing aircraft criteria. Therefore, the main research focus of the GARTEUR group on the rigid body RPC was to review existing fixed wing PIO criteria and to assess whether these criteria could be applied to rotorcraft. In this context, it should be mentioned that only Category I and Category II PIO criteria were investigated. According to McRuer [ref. 1], Category I refers to linear pilot-vehicle system oscillations, i.e. one can assume linear behavior of the pilot and control system. The most common cause associated with such PIOs is excessive phase loss (in frequency domain) or excessive time delay (in time domain), typically resulting in a destabilization of the closed loop pilot-vehicle system. Category II PIO or quasi-linear pilot-vehicle oscillations correspond to limit cycle oscillations of the pilot-vehicle system due to nonlinear control elements in the feedback system (such as rate and position limiters). The usual cause of category II PIO is a trigger event. Category III PIO covers severe pilot-vehicle oscillations, which are inherently non-linear and characterized by a transition from one transient response to another. The detection and modeling of transition physics in category III PIOs can be related to the vehicle (e.g. non-linear aerodynamics), to the flight control system state transition (e.g. mode switching) or the pilot-biomechanics (e.g. pilot pattern change). Category III PIO analysis was beyond the scope of the GARTEUR research activities.

3.1 Predicting RPC

Fixed-wing category I PIO occurrences are associated with poor handling qualities in the open loop system because the system has very limited phase margin or has a narrow bandwidth and is easily destabilized. This is also true for helicopters. From the multitude of PIO criteria defined for aircraft (see ref. 5 and ref. 1 for a good overview) two criteria have been selected by the GARTEUR group: 1) the bandwidth criterion and 2) the Gibson average phase rate criterion. The selection of criteria was based upon an analysis of aircraft criteria as given by ref. 10**.** There, a database of 207 aircraft configurations was used to assess the ability of different existing fixed wing criteria to correctly predict PIOs. The results showed that the most successful criterion to predict fixed wing PIO corresponds to Bandwidth/Phase delay criterion (86% correctly predict PIOs) followed by Gibson criterion (73%). Therefore, the GARTEUR group on rigid body RPC decided to first concentrate on these criteria. Sections 3.1.2 and 3.1.3 apply these criteria to the BO105 helicopter.

3.1.1 Experiments

To predict the BO105 model combinations which are RPC prone and RPC resistant using existing PIO criteria, a set of configurations were set up by Univ. of Liverpool and ONERA and implemented in the full-motion simulator of the University of Liverpool (see refs. 11 and 12). The design of the experiments was inspired by the work of GARTEUR group FM-AG12 on fixed wing aircraft [ref. 4]. Two different kinds of experiment were undertaken in the simulator: 1) display tracking task and 2) non display tracking tasks (manoeuvres). The display tracking task consisted of roll tasks being conducted with different configurations in advancing flight. Each run lasted for about one minute. During the flight the pilot had to track the given task as aggressively as possible and after each test run a PIO rating (PIOR) was given according to the PIO rating scale (see Figure 7 from ref. 13). After the tracking task was flown, the pilot had to concentrate on two manoeuvres: slalom (see Figure 8) and precision hover. These manoeuvres were designed according to the ADS-33 handling qualities standard [ref. 16] description. Table 2 summarizes the chosen configurations. C1 represents forward flight 65kts condition and C2 the hover, B=baseline model, A= augmented model, L,M,H FCS desired dynamics (low, medium, high); B,M,G expected behaviour (Bad, Medium, Good).

Condition	Helicopter	FCS Desired Dynamics (bandwidth)				Time Delay (msec)			Expected behaviour			Condition
C1	**B**aseline model **B**	N/A	Low **L**	Medium **M**	High **H**	0	100	200	Good **G**	Medium **M**	Bad **B**	C1B-G C1B-M…
	Augmented model **A**											
C2	**B**aseline model **B**	N/A	Low	Medium	High	0	100	200	Good	Medium	Bad	C2A-M-B C2A-H-G. .
	Augmented model A											

Table 2: Modified BO105 models for 'rigid body' RPC studies

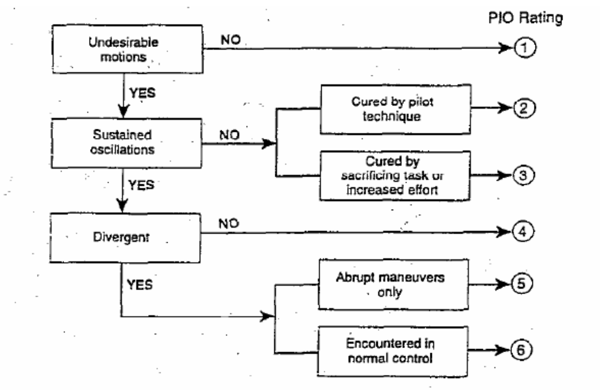


Figure 7 PIO rating scale [ref. 13]

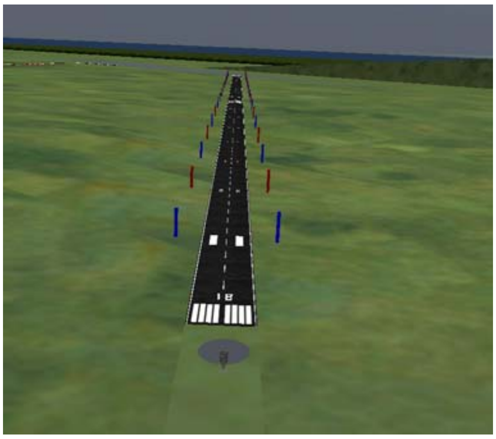


Figure 8 ADS-33 slalom manoeuvre in the simulator at Liverpool

3.1.2 Predicting Category I RPC - Bandwidth/Phase Delay Criterion

The bandwidth criterion was developed during the 1970's as a longitudinal handling qualities requirement, primarily for fighter aircraft [ref. 14] and was later introduced in the military standards MIL-STD-1797A [ref. 15]. Physically, the bandwidth is a measure of the maximum frequency below which the pilot can follow all commands and above which he cannot. Essentially, it is a measure of the quickness with which the aircraft can respond to an input: an aircraft with high bandwidth is described as agile with a crisp response; an aircraft with low bandwidth is more sluggish with a smooth response.

The criterion uses the bode plot representation of the aircraft response to pilot input (input expressed as control force or stick displacement). For example, Figure 9 plots the bode representation of the pitch response to control force for the BO105 with time delay included in the control system. The helicopter is disturbed from an initial hover condition by application of a sinusoidal input in longitudinal cyclic.

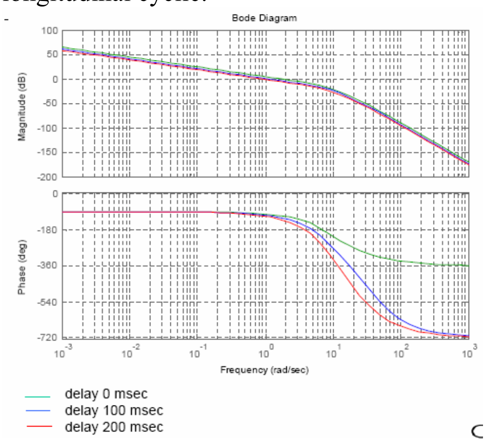


Figure 9 Bode plot of pitch response to pitch input for BO105 in hover

From this figure two parameters are needed for the calculation of the pitch axis bandwidth criterion: the bandwidth frequency $\omega_{BW\theta}$ and the phase-delay τ_p. The bandwidth frequency is defined as the frequency where the phase margin is 45 deg (when related to phase) or as the frequency where the gain margin is 6dB (when related to gain). Further, the phase delay parameter for the pitch attitude responses can be calculated as:

$$\tau_{p\theta} = \frac{-180\,\mathrm{deg} - \Phi(\omega = 2\omega_{180})}{2\omega_{180}}\frac{\pi}{180}(\mathrm{sec}) \qquad (7)$$

where ω_{180} is the frequency corresponding to a -180 deg phase delay and $\Phi(\omega=\omega_{180})$ the phase angle read at 2 ω_{180}. The phase delay is a measure of the steepness of the slope of the phase curve at the point where the output lags the input by 180 deg (neutral stability). As the pilot increases his gain in the task, he approaches the frequency where the aircraft responds *out of phase with the input*. His natural reaction is then to apply a "mental lead filter" to compensate for this phase shift. The success of this technique depends to a large degree on the response predictability: if the phase slope near the -180 deg point is shallow, minor control deviations in the vicinity of this frequency will cause minor changes in the phase shift and the "mental filter" will be predictable; if the phase slope near the -180 deg point is too steep, minor changes in frequency will cause major changes in the phase shift and the "mental filter" will be less predictable.

The bandwidth/phase delay requirement was adopted from the fixed wing to the rotorcraft configurations and introduced in the Aeronautical Design Standard ADS-33 [ref. 1]. However, while for fixed wing aircraft, the phase delay was correlated with the APC susceptibility and plotted as *APC boundaries* giving the phase delay as a function of the bandwidth frequency, for rotorcraft, RPC boundaries have never been defined. More precisely, the bandwidth/phase delay requirement as introduced in the ADS-33 does not relate to RPC susceptibility but only to *handling qualities boundaries* in charts representing the phase delay $\tau_{p\theta}$ as a function of bandwidth frequency $\omega_{BW\theta}$. Only a comment of caution is present in the ADS-33 stating that the rotorcraft may be PIO prone if the bandwidth defined by gain margin is less than the bandwidth defined by phase margin (i.e. $\omega_{BWgain} < \omega_{BWphase}$).

The bandwidth/phase delay criterion was applied to the BO105 for pitch and roll axes in hover and forward flight conditions using the database of cases flown in the simulator (see section 3.1.1). The theoretical predictions are presented in Figure 10 and Figure 11 as are the boundaries for fixed wing aircraft. Generally, one can see that low/medium dynamics associated with high time delays (bad configuration) result in a PIO prone system. Comparing the prediction of the bandwidth-phase delay PIO criterion as plotted against the fixed wing boundaries with the prediction of the bandwidth-phase delay requirements from Aeronautical Design Standard ADS-33E-PRF as represented in Figure 12 [ref. 16], one can see a relatively good agreement between the expected results. For example, according to the ADS-33E-PRF requirements, the designed FCS with no added time delay (C1A-M-G) is expected to provide Level 1 flying qualities in roll. With a 100msec-added time delay (C1A-M-M), they degrade to Level 2. According to the APC bandwidth-phase delay criterion, this latter configuration is still PIO resistant. A worse configuration with 200msec-added time delay (C1A-M-B) results in a marginally adequate to inadequate (borderline Level 2-3) handling qualities and a PIO prone configuration. On Figure 12 corresponding to the ADS-33 bandwidth requirements, it can be seen that for the roll axis, the borderline Level 2-3 corresponds roughly to the PIO pass/fail division.

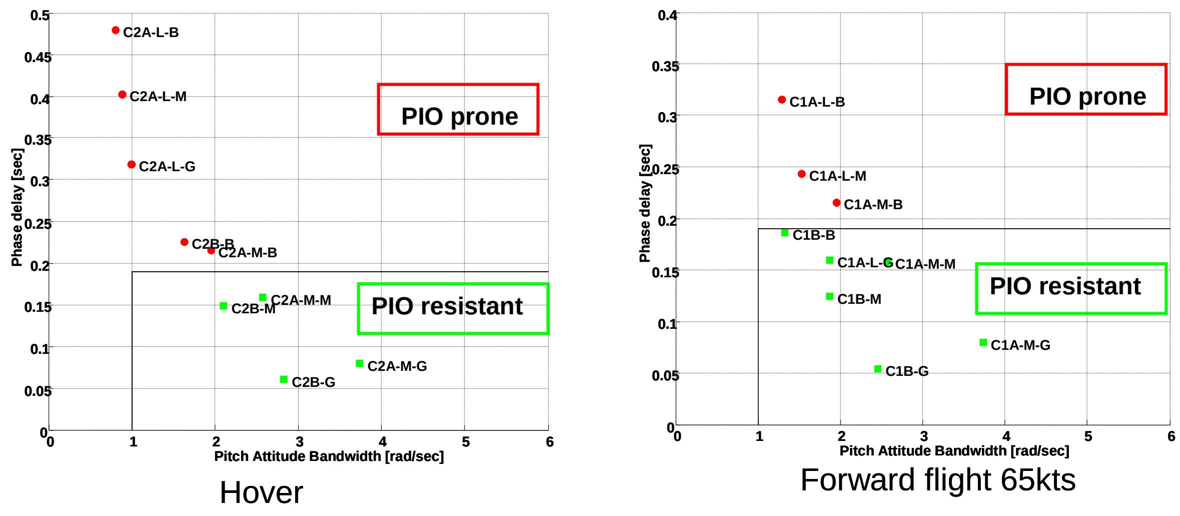


Figure 10 Bandwidth phase delay criterion for pitch axis – ONERA

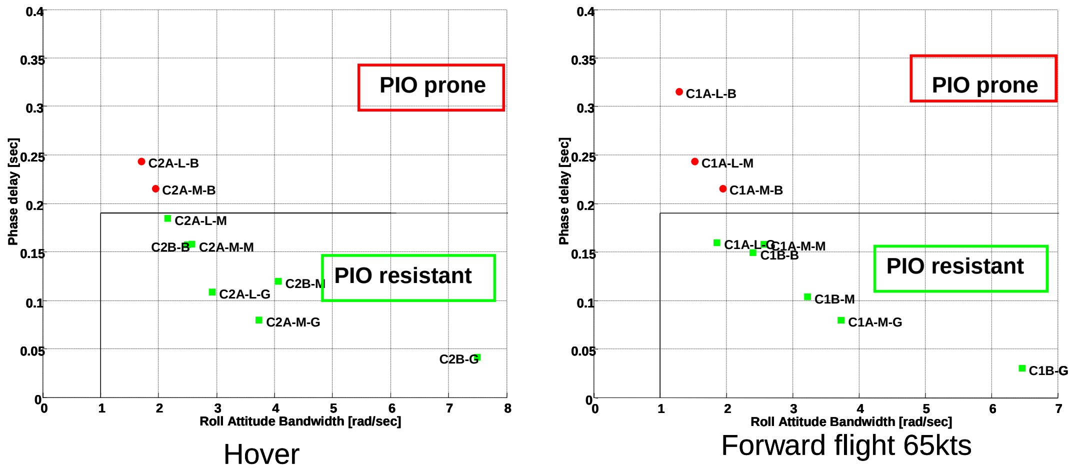


Figure 11 Bandwidth phase delay criterion for roll axis – ONERA

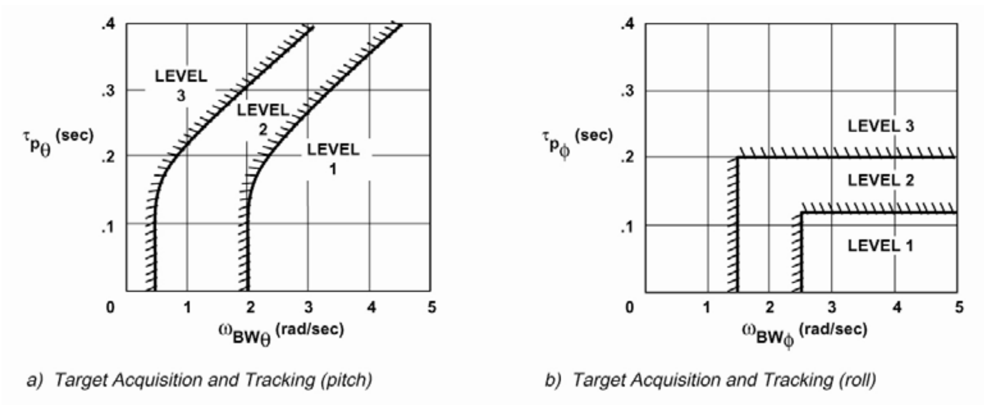


Figure 12 ADS-33 handling qualities bandwidth requirement for small-amplitude pitch (roll) attitude changes for hover and low speed [ref. 16]

The RPC theoretical predictions of Figure 10 and Figure 11 were compared to the piloted tests explained in Section 3.1.1. Figure 13 presents a sample of results obtained with the roll tracking task in forward flight. One can see a wide spread in ratings between the pilots (2 pilots). The results obtained suggest that assuming that the tasks and the evaluation procedure are well designed, more experiments with additional pilots should be conducted to reduce the spread in the ratings. Nevertheless, it is assumed that the calculated results are more or less representative, if complementary information such the maximum rating for all pilots in the same condition is also indicated. Indeed, if one pilot rates the system significantly better (e.g. PIOR 2) while the other pilot experiences a control loss (rating 6) then, despite the low mean rating, then a potential safety problem may still exist.

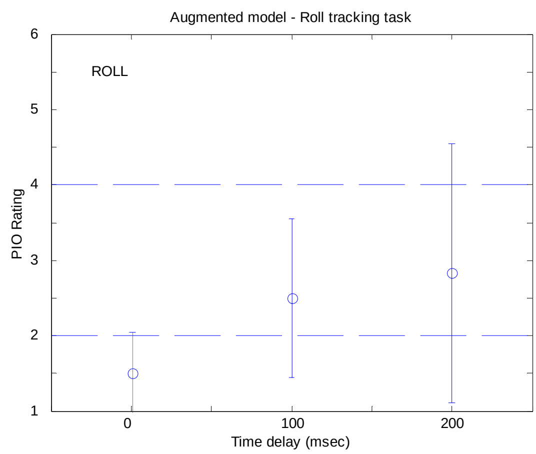


Figure 13 PIO ratings vs time delay –Roll tracking task

3.1.3 Predicting Category I RPC - Gibson Phase Rate Criterion

Gibson's work in the fixed-wing industry led to the definition of design guidelines for aircraft control, handling qualities and PIO susceptibility. One of most recent criterion for predicting Category I PIOs is the Gibson phase rate criterion [ref. 17]. The assumption in this criterion considers that when the aircraft response is 180 deg out of phase to the pilot commands the system is susceptible to PIOs. As long as the gain around this frequency is low enough, the aircraft response is low in magnitude so that a PIO is not encountered. Gibson gives PIO boundaries in a chart representing the average phase rate parameter as a function of the aircraft frequency when the response lags the pilot commands by 180 deg (see Figure 14). The average phase angle can be defined as:

$$PR = \frac{\Phi_2 - \Phi_1}{\omega_2 - \omega_1} \qquad (8)$$

where ω_1 and ω_2 represent points on the frequency response before and beyond ω_{180} and Φ_1 and Φ_2 are the corresponding phase. Usually, it is considered that $\omega_1=\omega_{180}$ and $\omega_2=2\omega_{180}$, this definition being equivalent to the phase delay parameter as used in the bandwidth criterion. In this case, equations (7) and (8) can be connected through the following relation:

$$\tau_{p\theta}[\text{sec}] = \frac{PR[\text{deg}/Hz]}{720[\text{deg}]} \qquad (9)$$

Figure 14 presents the Gibson phase rate criterion when applied to the BO105 in forward flight for pitch axis. Looking at this figure, one can see again that the most PIO prone configurations are C1A-L-M and C1A-L-B corresponding to low dynamics and high time delays and correspond to PIOR>3.

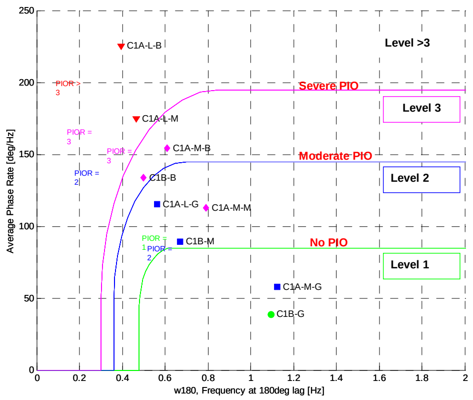


Figure 14 Gibson Average Phase Rate Criterion

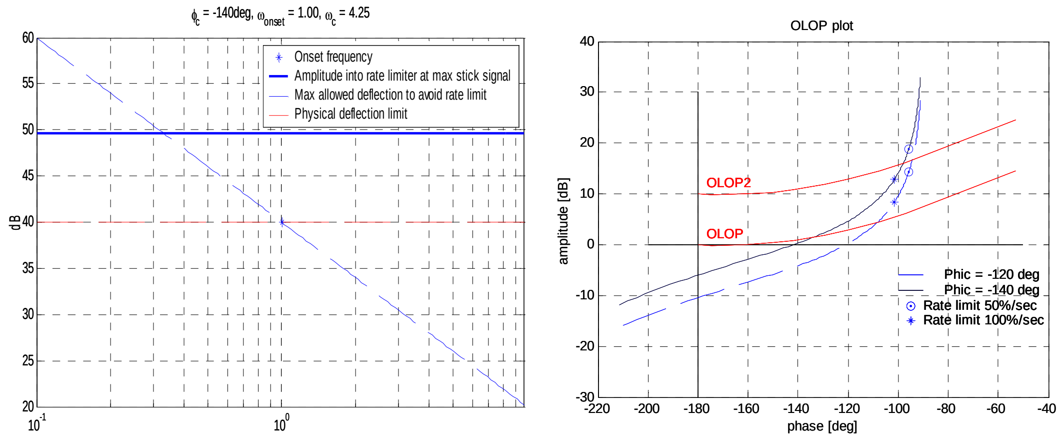
.

3.1.4 Predicting Category II RPC – OLOP Criterion

For the application of the OLOP criterion, the augmented model of the BO105 was used. Nonlinearities represented by maximum stick deflections and maximum rates are added to the model. The procedure for the application of the criterion is summarized below:

- Definition of a simple high gain pilot model based on the linear rotorcraft dynamics
- Calculation of the linear closed-loop frequency response from the stick input to the input of the rate limiter
- Determination of the close-loop onset frequency ω_{onset} considering stick and actuator deflection limits.
- Calculation of the linear open-loop frequency response and separation into amplitude $A_0(\omega)$ and phase angle $\Phi_0(\omega)$
- OLOP = $[\, \Phi_0(\omega_{onset}), A_0(\omega_{onset}) \,]$

Figure 15 presents the application of OLOP criterion for the BO105 roll axis in forward flight when a rate limit of 100 per cent of stick deflection per second, 50 per cent of stick deflection per second is introduced in the forward path of the flight control system. The RPC prediction is shown for a low pilot gain and a medium pilot gain corresponding to a cross-over phase of -120 deg and -140 deg respectively. From the test campaigns conducted at the University of Liverpool, with the display roll tracking task, the above configurations were rated respectively PIOR 1 and PIOR 2 by a low-gain-pilot, while a higher-gain-pilot gave the ratings PIOR 3 and PIOR 4 respectively. This suggests that the boundary lies somewhere between the original OLOP boundary and the modified OLOP2 boundary reported in Ref. 18, but further validation has still to be made.



Determination of closed-loop onset frequency **OLOP for the roll axis in 65kts forward flight**

Figure 15: OLOP criterion for the BO105 roll axis

4. THE CONCEPT OF BOUNDARY AVOIDANCE TRACKING FOR RPC ANALYSIS

The GARTEUR HC-AG16 group has concentrated furthermore on finding new concepts which are typically suited for predicting rotorcraft RPC. An example herein is the so-called concept of “boundary avoidance tracking” (BAT). This concept was thought recently for the fixed-wing aircraft [refs. 19, 20]. The present paper will extend this concept to rotorcraft configurations. The next paragraphs summarize the concept of BAT and how it was extended to helicopters.

Classically, pilot models used to describe the closed-loop pilot-vehicle interaction make the assumption that a pilot attempting to control an aircraft is always attempting to maintain a given condition (such as pitch attitude, flight path, all attitude or heading) – the so-called “point tracking” assumption. All PIO criteria derived up to date (including also the bandwidth and Gibson criteria) are based on this assumption and explain PIOs due to an extraordinary increase in the pilot gain that controls that point parameter up to the border where the pilot approaches the frequency where the aircraft responds out of phase to the input (see Figure 6 showing the principle of controlling the pitch attitude). Based on many discussions with the pilots, Gray [refs. 19, 20] considers that this assumption does not correspond to the pilots’ actual experience. He explains that “while pilots spend most of their time maintaining a variety of parameters” (point tracking), there are critical cases when the point tracking parameter is of secondary interest to the pilot. Such a case can be a dangerous PIO where it seems that the pilot is tracking something more than a point parameter. From the discussions with the pilots, Gray concluded that, for them, a PIO represented a succession of opposing events wherein they continuously attempt to survive by alternatively attempting to track the opposing risks describing those events. In other words, the pilots were tracking a hazard, expressible as a boundary, in an attempt to prevent a condition corresponding to that boundary. In this way, one can better model the pilot behavior in a PIO, not as traditionally done by means of a high gain tracking of a single parameter but by boundary-avoidance tracking (BAT).

At TUD, the BAT concept was applied to helicopters (see refs. 21, 22) Consider next this concept applied to the investigation of a RPC problem in the pitch axis. In the classical point-tracking model (see Figure 6) the pilot is trying to control the helicopter pitch attitude θ by feeding it back to obtain the error θ_{err} before applying the longitudinal cyclic θ_{1s}. Figure 16 presents the concept of the boundary tracking model as proposed by Gray [ref. 19] and applied to a helicopter model.

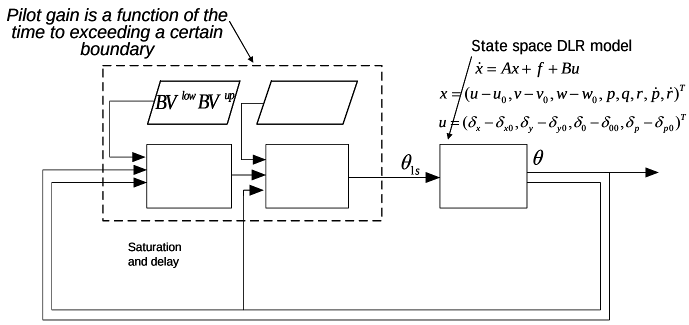


Figure 16 Boundary-tracking concept

One can see that the helicopter pitch attitude and rate are fed back and used by the pilot to determine how much time is needed to reach the boundary - the so-called time to boundary t_b. The time to boundary is in fact the source in provoking a PIO and can be calculated as:

$$\begin{aligned} &if\; q<0 \quad t_b = \frac{BV^{low} - \theta_{rel}}{q} \\ &if\; q>0 \quad t_b = \frac{BV^{up} - \theta_{rel}}{q} \end{aligned} \qquad (10)$$

Equation (10) depends upon whether the pilot is approaching a lower BV^{low} or an upper pitch attitude boundary BV^{up}. The notations in eq. (10) refer to imposed values in :1) an upper BV^{up} and a lower boundary value BV^{low} for the relative pitch attitude $\theta_{rel} = \theta - \theta_{trim}$ that show the boundaries between which the pilot can move without threat; 2) a maximum t_{max} and a minimum t_{min} time with the signification that when the $t_b \leq t_{max}$ the pilot is moving towards the boundary and there is maximum threat for "hitting" the boundary, when $t_{max} < t_b < t_{min}$ then the pilot is not threatened by the boundary but he is aware of it in his actions and finally when $t_b \geq t_{min}$ then the pilot is not threatened by the boundary. Depending on this time to the boundary, the pilot will feed back the helicopter response with a boundary feedback BF value before reaching the upper/lower boundary. The values of BV in the pitch axis vary between $\pm 14^o$, $\pm 10^o$, $\pm 8^o$, $\pm 5^o$.

4.1 Experiments on BAT

To understand the concept of BAT, a series of pull-up manoeuvres were tested in the simulator at Liverpool in two test campaigns: 1 (1 pilot) and 2 (1 pilot repeated 2 times). Figure 17 presents the design of a BAT experiment. Mainly, the pilot had to fly a sinusoidal path (continuously pull-up/pull down manoeuvres) corresponding to a "longitudinal cyclic input marker" seen on the screen. The marker was moving between two boundaries. The boundaries were narrowed to increase the aggressiveness of the manoeuvre up to the limit of losing control (inducing RPC). To reduce the predictability of the path, the sinusoidal path was composed of a series of sine functions of different frequency.

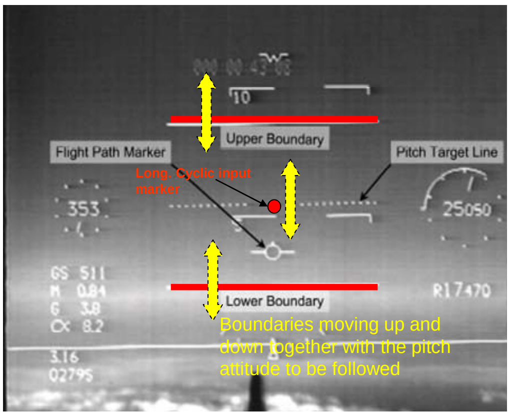


Figure 17 Test course for the BAT concept in the pitch axis

4.2 Results on BAT concept for helicopters

For helicopters, the simulator campaigns as described in section 4.1 showed three important characteristics of the BAT concept:

1) Depending on the time and distance to the boundary, the pilot used both the point tracking and the boundary avoidance strategies. Therefore, the model of Gray as given by Figure 16 was extended to a combined point tracking/boundary tracking model as seen in Figure 18. The point tracking model was first built in the form of a Proportional Derivative PD controller monitoring all helicopter axes. The crucial question to be answered when building this new model was when did the pilot switch between one concept and the other? The simulations in the Liverpool simulator proved that when the pitch attitude was between halfway and 2/3 of the distance between the point tracker and the closest boundary the model had to switch from the point tracking to the boundary tracking concept (see Figure 19).

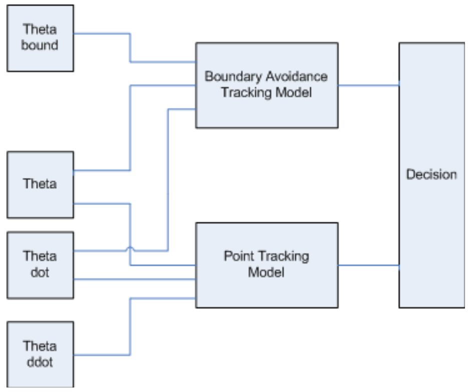
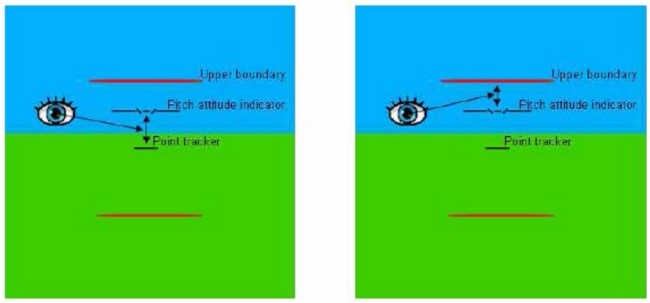


Figure 18: Combined point tracking and boundary avoidance tracking modelling for RPC prediction-TUD



(a) Pilot focusses on the distance to the point tracker. (Point Tracking)

(b) Pilot focusses on the distance to the nearest boundary. (Boundary Reactive Control)

Figure 19 Switching between the point tracking and boundary tracking modeling-TUD

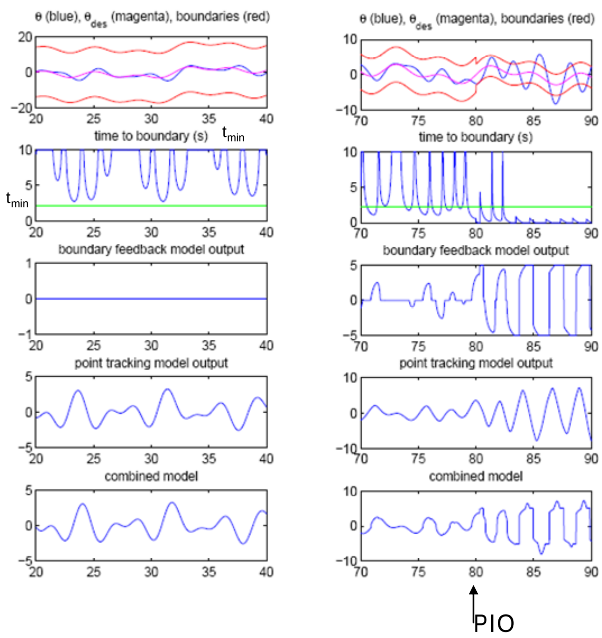
2) The second conclusion of the simulator tests was that, the time delay τ_{sys} introduced to trigger the RPC influenced the aggressiveness with which the pilot was flying the manoeuvre as he was approaching boundaries. As the pilot commented himself, he was not really threatened by the boundaries as long as the maneuverability was sufficient. When the time delay added to the system was increased, it was observed that the pilot started to respond to the boundaries earlier.

This observation gave reason to question whether the value of t_{min} should be, as initially assumed by Gray in ref. 19, constant. The following reasoning is presented: The pilot is assumed to passively perceive time delay of the system he is controlling. The result is that the pilot knows, or feels, that the response of the vehicle takes place at a certain amount of time after he has commanded the action. If he is approaching a boundary, he will have to take this amount of time delay into account in order to be able to safely avoid the boundary. The safety margin the pilot has to maintain (i.e. the time between control input and foreseen boundary violation) is at least equal to the effective time delay of the pilot-vehicle system. This margin is in fact the threshold for boundary avoidance tracking, t_{min}. Therefore, a new assumption was made w.r.t. the initial concept, i.e., for helicopters the effective time delay of the controlled system τ_{sys} is proportional to the minimum time to boundary t_{min}, i.e.:

$$t_{min} \propto \tau_{sys} \qquad (11)$$

This means that if a pilot is controlling a hypothetical system with no time delay at all, he would not have to maintain a margin. The exact relation between effective time delay and t_{min} is still under investigation. Because the value of t_{min} depends on psychological processes, it may vary for different pilots. Most probably, the value is even different for one pilot, depending on his alertness. For example, a pilot may become less sensitive and maintain a lower value of t_{min}, if he becomes fatigued after many consecutive hours of flying. This effect is subject to research as well.

3) The third observation of the simulator tests was that if the time to boundary t_b is smaller than the minimum time to boundary $t_b < t_{min}$, a RPC onset is initiated by the pilot. For example Figure 20 shows the predicted results of the pitch manoeuvre in forward flight with time delay of 200 msec using the model of Figure 18. One can see that for the interval 70 to 90 seconds a RPC onset has been initiated by the pilot and that this corresponds to the time to boundary $t_b < t_{min}$ from the 80th second of the simulation.



(a) Interval from 20s to 40s. (b) Interval from 70s to 90s.

NO PIO PIO ONSET

Figure 20 Simulator results of BAT concept, pitch manoeuvre on forward flight 65kts

5. CONCLUSIONS

Concluding, the exercise of the paper was to present the results obtained by the GARTEUR HC-AG16 group on predicting rigid body RPC and to develop new perspectives on analysing pilot behaviour during rotorcraft hazardous RPC that may lead to innovative criteria and techniques for RPC analysis. The results on rigid body RPC analysis demonstrate that:

- Theoretical prediction of Category I RPC with the fixed wing bandwidth/phase delay criterion and Gibson phase rate criterion show that a system with low and medium dynamics associated with high time delays result in a RPC prone system.
- Comparing the prediction of the bandwidth/phase delay PIO criterion as plotted in the fixed wing boundaries with the prediction of the bandwidth-phase delay requirements from Aeronautical Design Standard ADS-33E-PRF shows a relatively good agreement between the expected results.
- Validation of the theoretical predictions of Category I RPC with simulator experiments shows a wide spread in the pilot PIO ratings. This suggests that, assuming that the tasks and the evaluation procedure are well designed, more experiments with additional pilots should be conducted to reduce the spread in the ratings.

- The concept of boundary avoidance tracking (BAT) was extended to rotorcraft applications and tested in the simulator. The results show that BAT concept can be applied to helicopters, the condition for a RPC onset depends on the value of the minimum time to boundary t_{min} which has to be proportional to the system time delay τ_{sys}. The simulator tests on BAT concept showed that the pilot uses both the point tracking concept or the boundary avoidance concept depending on the time and distance he has to reach that boundary. For a pitch axis manoeuvre, it was proved that, when the pitch attitude is between halfway and 2/3 of the distance between the point tracker and the closest boundary, the pilot is switching from the point tracking strategy to the boundary tracking. The closer are the boundaries, the higher the tendency to develop RPC. However, it appeared that the pilot was not really threatened by the boundaries as long as the maneuverability was sufficient. It appears that the primary condition for developing a RPC is the system time delay and not the approach to boundaries.

Further research is needed to refine the adjustment of the APC criteria boundaries to rotorcraft requirements. Concerning the BAT concept, an interesting extension of the theoretical modelling is to use instead of a PD model the structural pilot model of Hess.

References

1. McRuer, D.T., et al., (1997), “AVIATION SAFETY AND PILOT CONTROL. Understanding and Preventing Unfavorable Pilot-Vehicle Interactions”, *ASEB National Research Council*, National Academy Press, Washington D.C., 1997
2. Pratt, Roger W., “Flight Control Systems-practical issues in design and implementation”, IEE Control Engineering Series 57, TJ International, Padstow, 2000
3. Hamel, Peter G., “ROTORCRAFT-PILOT COUPLING A Critical Issue for Highly Augmented Helicopters?”, paper presented at the AGARD-FVP Symposium “Advances in Rotorcraft Technology”, 27-30 May 1996, Ottawa, Canada
4. GARTEUR FM-AG12 “Pilot-in-the-Loop-Oscillations – analysis and test techniques for their prevention, phase I”, Workshop, 11 Oct. 2001, EADS Manching, Germany
5. GARTEUR FM-AG15 “Pilot-in-the-Loop-Oscillations – analysis and test techniques for their prevention, phase II”, Workshop, 10 May 2007, Saab AB Linköping Sweden
6. GARTEUR Helicopters AG-16 “Rigid body and aeroelastic rotorcraft-pilot coupling – prediction tools and means of prevention” https://exsites.dlr.de/ft/garteurag16
7. Goetz, J., “Bo-105 State Space Model”, GARTEUR HC-AG16, WP3 working paper, Nov. 2005
8. Benoit B., et. al. HOST, a General Helicopter Simulation Tool for Germany and France. 56th American Helicopter Society Annual Forum, Virginia Beach, Virginia, May 2000
9. Padfield, G.D., White, M.D., “Flight Simulation in Academia; HELIFLIGHT in its first year of operation - The Challenge of Realistic Rotorcraft Simulation”, Royal Aeronautical Society Conference, London, November, 2001
10. Mitchell, D.G., Klyde, D.H., 1998, “A critical examination of PIO prediction criteria”, AIAA-98-4335, 1998
11. Dieterich, Oliver, et. al., “Adverse Rotorcraft-Pilot Coupling: Recent Research Activities in Europe”, the 34th European Rotorcraft Forum, September16-19, 2008, Liverpool, UK
12. Jump, Michael, et. al., “Adverse Rotorcraft-Pilot Coupling: Test Campaign Development at the University of Liverpool”, the 34th European Rotorcraft Forum, September16-19, 2008, Liverpool, UK
13. Powers, B., “Space Shuttle Pilot-Induced-Oscillations Research Testing”, AGARD 262, 1984
14. Hoh, R.E., Hodgkinson, J., “Bandwidth – A Criterion for Highly Augmented Airplanes”, AGARD CP-333, April 1982
15. MIL-STD-1797A (USAF), “Military Standard: Flying Qualities of Piloted Aircraft”, Wright Patterson AFB, 1990
16. Anon., Handling Qualities Requirements for Military Rotorcraft, Aeronautical Design Standard ADS-33E-PRF, Performance Specification, US Army AMCOM, Redstone, Alabama, March 21, 2000
17. Gibson, J.C., “Development of a methodology for excellence in handling qualities design for fly by wire aircraft”, Delft University press dissertation, 1999
18. Wilmes, T., Duda, H.., Investigation of electronic filters to prevent aircraft-pilot-coupling, Technical Report IB 111-98/29, Institut fur Flugmechanik, Braunschweig, Nov. 1998.

19. Gray III, William R., “Boundary-Avoidance Tracking: A New Pilot Tracking Model”, AIAA Atmospheric Flight Mechanics Conference, 15-18 August 2005, San Francisco, AIAA 2005-5810
20. Gray III, William R., “Boundary Avoidance Tracking and its Use in Handling Qualities Evaluations”, 18th SFTE (EC) Symposium, 11-13 June 2007, Madrid, Spain
21. De Groot, S., Pavel, M.D., “New insights into pilot behaviour during hazardous rotorcraft pilot induced oscillations”, paper no. 3HQ1, 62nd American Helicopter Society Annual Forum, May 9-11, 2006, Phoenix, Arizona
22. Brinkerink, N.P., “Simulation of Boundary Reactive Control to Predict Inadvertent Rotorcraft-Pilot Coupling”, TUD MSc Report, June 2008
23. Reichert, G., “Stabilitatsprobleme mit dem Versuchshubschrauber Boelkow Bo 46”, Provate Communication, Braunschweig, 23 Aug. 1996
24. Gabel, R., et. Al., “Test approaches to external sling load instabilities”, 24th Annual Forum AHS, 1968, paper 230
25. N.N., “Lockheed flight testing AH-56 with modified control blades”, AW&ST, 30 March 1970, pp 66-67
26. Kaplita, T.T., “Helicopter simulation development by correlation with frequency sweep flight test data”, 45th Annual Forum AHS, 1989, pp. 681-692
27. Buchacker E., “Experience with SIFT Flight Test Techniques at the German Air Force Flight test center”, AGARD-CP-333, paper 24, june 1982
28. Tischler, M.B., et. al., „Flying quality analysis and flight evaluation of highly augmented combat rotorcraft“, AIAA J. Guidance, Vol 14, no 5., pp 954-963, sept-oct 1991
29. Parham, T., et. al., “V-22 pilot in the loop aeroelastic stability analysis”, 47th Annual forum AHS, Phoenix, May 6-8, 1991, pp. 1307-1319
30. Pausder, HJ, Blanken CL, “Investigation of the Effects of Bandwidth and time delay on helicopter roll-axis handling qualities”, NASA CP-3220, Jan 1993
31. Bouwer, G., et. al., “Smart Helicopter Concept – Handling Qualities database for hover and low speed flight”, AGARD-CP-592, paper 11, dec. 1996
32. Lantzsch, Robin, Wolfram Jens, Hamers Mario, “Increasing Handling Qualities and Flight Control Performance using an Air Resonance Controller”, 64th Annual Forum AHS, Montréal, Canada, April 29 – May 1, 2008
33. Walden, Barry R., “A Retrospective of Pilot-Structural Coupling Instabilities in Naval Rotorcraft”, 63th Annual Forum AHS, Virginia Beach, VA, May 1-3, 2007