Rotorcraft-Pilot Coupling Research in Europe: A Success Story in Collaboration

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ABSTRACT

For augmented helicopters with modern flight control systems, unintended and unexpected oscillations or divergences of the pilot-rotorcraft system have become an increasingly critical issue. Especially the rapid advances in the field of high response actuation and highly augmented flight control systems have increased the sensitivity to aspects that lead to unfavourable Aircraft-Pilot Coupling (APC) and Rotorcraft-Pilot Coupling (RPC). The understanding, prediction and prevention of adverse RPCs is a challenging task requiring the analysis and simulation of the complete closed loop system consisting of pilot – control system – rotorcraft. In Europe, comprehensive research activities were launched by the GARTEUR HC AG-16 action group (2005-2008) in order to improve the physical understanding of RPCs. Overall objectives of GARTEUR HC AG-16 were the definition of criteria for quantifying the helicopters' susceptibility to RPC and the establishment of guidelines for preventing or suppressing critical RPC incidents in future, thus contributing to increased helicopter operational safety. The GARTEUR research was further continued under the umbrella of the 7th European Framework Programme (FP7) in the project ARISTOTEL - Aircraft and Rotorcraft Pilot Couplings – Tools and Techniques for Alleviation and Detection (2010-2013). Regarding numerous flight events in the past, several types of RPCs have been observed which can be differentiated by the frequency contents as well as by the underlying physics and human behaviour. Focus in the GARTEUR HC AG-16 group was given on the one hand to RPC phenomena in the frequency range up to approximately 1 Hz and on the other hand to coupling phenomena approximately between 2 Hz and 5 Hz. This paper presents an overview of the various numerical and experimental activities of research. Selected results are highlighted and discussed demonstrating the used approach to investigate different RPC phenomena in a schematic manner.

1 INTRODUCTION

1.1 Adverse Interaction of Pilot with Rotorcraft

Causes and remedies for oscillations or divergence phenomena due to adverse vehicle-pilot couplings draw increased attention during the last decades [1]. These events may be better known in the aircraft and rotorcraft community as Pilot Induced Oscillation (PIO) and Pilot Assisted Oscillation (PAO), whereas divergence-type events are less known in practice.

In Europe, the "Group for Aeronautical Research and Technology in Europe" (GARTEUR) has launched comprehensive research activities in the GARTEUR HC AG-16 (Helicopters Action Group 16) in order to improve the physical understanding of RPCs and develop guidelines to prevent and suppress critical RPCs. GARTEUR is a organisation in Europe having as objective to mobilise research establishments, industry and academia in Europe in critical areas in aeronautics, stimulating advances in Europe in this field. GARTEUR HC AG-16 was established to advance the state of the art in predicting unfavourable RPCs.

Based on numerous flight experiences in the past, different types of RPCs have been observed, which were simplified in this GARTEUR action group research to 'rigid body RPCs' – the scope of flight dynamics – and 'aero-elastic RPCs' – the scope of aero-servo-elasticity. It is assumed that a certain overlap between these two RPC categories exists but within this GARTEUR action group, these two types were distinguished by different non-overlapping frequency ranges as follows:

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- The lower frequency range in the vicinity of and below 1Hz is attributed to adverse coupling phenomena dominated by helicopter low frequency dynamics i.e. the field of flight dynamics, by the flight control system and by an ‘active’ pilot concentrating on performing his mission task by actively manipulating rotorcraft controls.
- The higher frequency bandwidth at approximately 2Hz up to 8Hz is characterised by higher helicopter frequency dynamics i.e. the inclusion of elastic airframe and main rotor blade modes, by a ‘passive’ pilot subjected to vibrations which are too high in frequency to adequately be reacted by human beings and by the cockpit controls layout affecting the pilots inertial response on the helicopter control elements.

For the overlap between 1Hz and 2Hz a merge of phenomena leading to a mix of models and procedures is expected. Table 1 summarises the major distinctions between the rigid-body and aero-elastic RPC.

	‘Rigid Body RPC’	**‘Aero-elastic RPC’**
Frequency Range	Below 1Hz	Between 2Hz and 8Hz
Pilot Characteristics	‘Active’ pilot concentrating on a task of a mission	‘Passive’ pilot subjected to vibrations
Control Oscillations	PIO – Pilot Induced Oscillations	PAO – Pilot Assisted Oscillations
Helicopter Dynamics	Flight dynamics	Structural dynamics
Critical Components	Flight control system	Airframe modes

Table 1: Characterisation of ‘rigid body’ and ‘aero-elastic RPC’

1.2 GARTEUR HC AG-16 Action Group

As regards communication GARTEUR regularly presents its organisation, provides the latest achievements obtained through its activities and outlines its orientations [2] [3] [4]. The overall objectives of GARTEUR HC AG-16 consisted in the establishment of guidelines for the development of means to prevent or suppress critical RPC incidents in the future, thus contributing to increased helicopter operational safety. In detail, these objectives were:

- Improvement of the physical understanding of RPC
- Definition of criteria to quantify the susceptibility to RPC
- Development of prediction methods for RPCs
- Validation of prediction methods and criteria
- Development of preliminary guidelines/recommendations/methods for RPC prevention.

Participating partners of the action group covered five nations as well as industry, aerospace research establishments and universities:

- Airbus Helicopters AHD (technical co-ordinator) and DLR from Germany;
- ONERA from France;
- NLR and the Technical University of Delft (TUD) from the Netherlands;
- Politecnico di Milano (POLIMI) and Università Roma Tre (UROMA3) from Italy;
- University of Liverpool (UoL) from the UK.

More detailed information of the various activities can be found in the following papers disseminated by this action group for ‘rigid body RPC’ [5], ‘aero-elastic RPC’ [6] and related simulator testing [7].

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2 ROTORCRAFT MODEL DATABASE

In order to foster synergies between the different working groups, research activities focused on the BO105 rotorcraft, see Figure 1, and its various characteristics compiled by a common effort of AHD and DLR to a comprehensive data collection. The BO105 database consisted of the following five partitions allowing to set up rotorcraft models spanning from low order flight dynamic models up to high order aero-servo-elastic models, see Figure 2 and Figure 3:

- BO105 global data
- BO105 flight test database
- BO105 state space model
- BO105 elastic main rotor data
- BO105 elastic airframe data

The common and comprehensive rotorcraft database of the BO105 accessible by all partners offered the following advantages:

- Focus was put on direct comparison of methods and tools as the underlying rotorcraft data were the same for all partners.
- The methodological gap between 'rigid body RPC' and 'aeroelastic RPC' could be easily bridged by simply exchanging the numerical rotorcraft model.

Furthermore, the usage of the BO105 as representative rotorcraft allowed also the consideration of extensive research work done in the past and published in open literature.

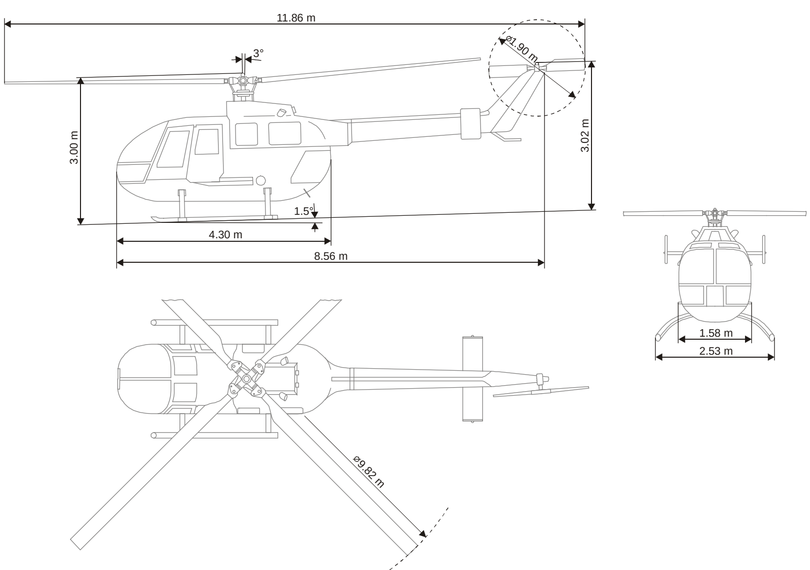

Figure 1: Three view drawing of the BO105

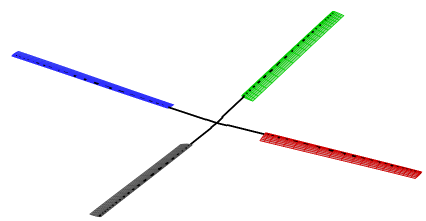

Figure 2: Aeroelastic main rotor model

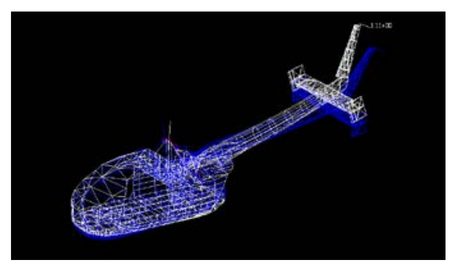

Figure 3: Vertical bending mode, 5.80 Hz

3 'RIGID BODY RPC'

The label 'rigid body RPC' is used in this paper in the sense of conventional RPC i.e. the pilot acting in a conscientious manner in order to fulfill mission control tasks and hereby failing in doing so. Typically the related frequency range of pilot action covers up to approximately 1Hz due to physiological and other limits of human beings. The wording 'rigid body' refers to the rotorcraft considered as rigid system which might not be totally true as e.g. rotor cyclic flapping can be accounted for by additional degrees of freedom. In fact, the peculiarities of main rotor aerodynamics and dynamics lead to significant differences in the behavior of rotorcraft compared to fixed wing aircraft. Figure 4, [8], presents the classification of

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‘rigid body RPC’ used in the ARISTOTEL project [9] as follow on of this action group. *Extended* ‘rigid body RPC’ are related to the extension of a classical 6-degree of freedom body modelling to the low-frequency modes of the rotor dynamics, the control actuators dynamics, the SAS dynamics effects or the digital system time delays. This class of RPCs can be seen as the blending area between rigid body and ‘aero-elastic RPCs’ and will need special tools and methods for analysis.

3.1 Methodological Approach

Extensive work was performed in the past with respect to RPC in the fixed wing area, e.g. by the former action groups GARTEUR AG FM-12 [10] and FM-15 [11] e.g. developing a dedicated PIO toolbox. In the action group presented in this paper, the methodology of checking PIO criteria for rotorcraft usage was reviewed. The numerical rotorcraft models were modified by introducing an artificial flight control system for a large bandwidth of flight dynamic characteristics suitable for RPC investigations. Then, the modified rotorcraft models were imported into the simulator and flight tested by professional test pilots. The pilots rated the different helicopter models based on a PIO rating scale allowing to cross-check the ratings with the predictions obtained by the different PIO criteria. In case of insufficient correlation levels, the question how to modify the criteria in order to better fit the experimental results was addressed.

The action group considered as well the classical McRuer’s division of RPCs [12] according to the degree of non-linearity of the pilot vehicle system (PVS). Category I refers to linear pilot-vehicle system oscillations, i.e. assuming 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.

3.2 Rotorcraft Model Preparation

At the beginning, the partners compared their rotorcraft models with respect to eigenvalues (pole maps), responses to pilot inputs according to the flight test database and to the results of different PIO criteria. Observed differences are mainly due to varying order of the models e.g. eighth order model (TUD), tenth order model (DLR) or twelfth order model (ONERA). Two flight conditions have been analyzed in detail: hover and level flight 65kts. Furthermore, a simple flight control system of RCAH type (rate command – attitude hold) was introduced into the numerical model of the BO105. The designed FCS had tunable feed-forward and feedback gains to provide the model with varying flying qualities which comply with the ADS-33 [13] requirements from Level 1 to Level 3. In addition, the ability to introduce time delays to the model control loop was provided to create vehicles of different RPC proneness. The numerical flight control system allows the dynamic behavior of the BO105 model to be modified in a straight forward manner as presented below in Table 2.

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

Table 2: Modified BO105 models for ‘rigid body’ RPC studies

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3.3 'Active' Pilot Model

In literature, a large variety of pilot models and related underlying schemes are available e.g. the classification into compensatory[1], pursuit[2] and precognitive[3] pilot control behaviour. Most relevant PIO pilot models can be partitioned into:

- Isomorphic models: Isomorphic models refer to models in which some effort has been directed toward explicitly modelling the dynamics of the human sensory and control output systems.
- Algorithmic models: Algorithmic models are created through the use of control systems that have been used for non-human controllers e.g. optimal control model (OCM).
- Behavioural-based models: Behavioural-based models rely upon novel and often detailed representations of human signal processing behaviour e.g. fuzzy logic or neural net models.

In this action group, the partners concentrated on modelling the pilot behaviour in a cross-over model belonging to compensatory control and isomorphic models. An alternative approach in terms of the so-called "boundary avoidance tracking" (BAT) model was investigated by TUD. In this model, PIO is understood 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. Figure 5 presents the concept of the boundary tracking model applied to a rotorcraft model as adapted from Gray [14].

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 if it is too small for the pilot to react in time. Simulator tests were used in order to determine the adequate parameter of the models related to on-set of PIO. In the follow-on project ARISTOTEL the BAT concept was related to the 'Optical Tau' theory developed at University of Liverpool [15]. BAT assumes that during an A/RPC event, the pilot behavior is more like tracking and avoiding a succession of opposing events which can be described as boundaries. Tau theory is based upon the premise that purposeful actions are accomplished by coupling the motion under control with either externally or internally perceived motion variables. Results have shown that when, pilots fly a roll-step maneuver (see Figure 15), there is a close correlation between the optical-tau and BAT.

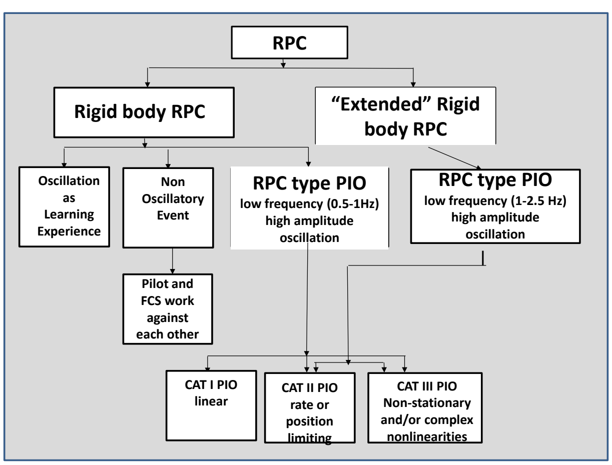

Figure 4 'Rigid body RPCs' [8]

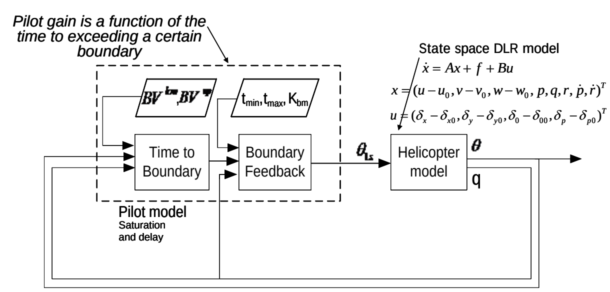

Figure 5: Boundary-avoidance tracking concept

[1] The pilot exerts continuous control on the aircraft so as to minimize system errors in the presence of commands and disturbances.
[2] By virtue of display human performance during pursuit behaviour improves with respect to the compensatory tracking behaviour.
[3] When complete familiarity with controlled dynamics and entire perceptual field is achieved, the highly-skilled human pilot can generate neuromuscular commands properly timed, scaled and sequenced.

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3.4 RPC Metrics and Application of PIO Toolbox

Fixed-wing category I PIO occurrences are associated with poor handling qualities in the open loop system because the system features very limited phase margin or narrow bandwidth and can thus easily be destabilized. This relationship is assumed to be also true for rotorcrafts. Thus, the action group activities concentrated first on PIO criteria characteristics developed for fixed wings and now applied to rotorcrafts. From the multitude of PIO criteria defined for aircraft, two criteria will be presented shortly in this paper: The bandwidth criterion for Cat I PIO and the Open Loop Onset Point criterion (OLOP) for Cat II PIO.

..3.4.1 Category I PIO: Bandwidth Criterion

The bandwidth criterion or more precise the bandwidth/phase delay criterion uses the bandwidth as 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. Two parameters are needed for the application of the bandwidth criterion: the bandwidth frequency $\omega_{BW\theta}$ and the phase-delay τ_p.

The bandwidth/phase delay requirement was adopted from the fixed wing to the rotorcraft configurations and introduced in the Aeronautical Design Standard ADS-33 [13] 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 τ_p 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. $\phi_{BWgain} < \phi_{BWphase}$). The theoretical predictions for the pitch axis are presented in Figure 6 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. 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 in a PIO prone configuration.

..3.4.2 Category II PIO: OLOP Criterion

The OLOP location in a Nichols chart is an indicator of the magnitude of the additional time delay due to rate limiting onset. The primary effect caused by the activation of a rate limiter is a strong increase in phase lag and a slight decrease in amplitude. If the OLOP is located at high amplitudes, the additional phase delay causes an increase in the closed-loop amplitude. This increase in closed-loop amplitude provokes stronger rate saturation and, therefore, a further increasing phase delay. This mechanism can lead to closed-loop instability.

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 application of OLOP is dependent on three major factors: pilot model, rate limit, and stick input amplitude. Figure 7 presents the OLOP criterion results 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. The results of the simulator test campaigns conducted at the University of Liverpool suggested that the boundary is located somewhere between the original OLOP boundary and the modified OLOP2 boundary (OLOP2 is derived from the initial OLOP with a 10dB gain shift).

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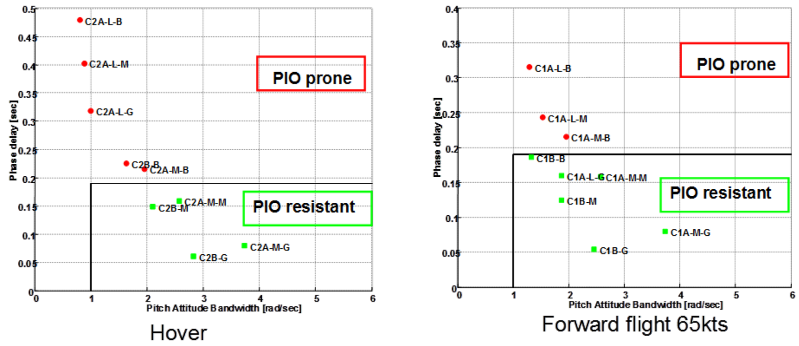

Figure 6 Bandwidth phase delay criterion for pitch axis – ONERA results [5]

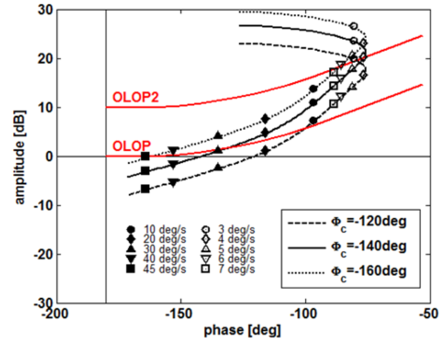

Figure 7: Roll axis OLOP at hover flight [5]

3.5 Performed Work and Conclusions on Rigid-body RPC

The three partners TUD, ONERA and UoL performed comprehensive and complementary 'rigid body RPC' studies based on the BO105 models. Basic activities such as flight dynamics modeling overlapped between partners' work for verification purposes. Furthermore, the partners investigated special issues in a complementary manner for increased synergy:

- TUD: Adaption of boundary avoidance tracking method to rotorcraft problems, comparison of predictive performance with point tracking methods
- ONERA: Application of PIO toolbox to rotorcraft problems, hereby also exploiting gained knowledge within action group FM AG-12 on fixed wing problems
- UoL: Focus on preparing and implementing the BO105 flight dynamics models for simulator operations, set-up of PIO test cases for simulator operation

In this context, it should be mentioned that the availability of the PIO toolbox proved to provide high synergy as fixed wing criteria could directly be applied to rotorcraft problems including comparison with simulator tests. The toolbox could be successfully applied for this purpose; nevertheless the limitations of the experimental database (e.g. number of pilots, test campaigns etc.) suggested to extend the activities in order to improve confidence in conclusions from statistical point of view.

4 AEROELASTIC RPC

Human bodies tend to show resonance phenomena in the vicinity of 3 Hz which might affect pilot arm and hand motions while controlling the rotorcraft. Thus, candidate structural modes which can interact with these human body modes due to their frequency placement are on the one hand the fundamental airframe bending modes in either vertical or lateral direction leading to related pilot seat and thus pilot body accelerations. On the other hand, main rotor cyclic lead-lag modes which couple with airframe roll motions on ground and in flight can lead to pilot seat accelerations in lateral direction as well. Depending on vibration characteristics, the pilot provides feedback to the primary control elements which might either increase or reduce the initial disturbance – equivalent to destabilization or stabilization. For simplicity, the partners decided to focus mainly on an 'aero-elastic RPC' phenomenon which is called "vertical bouncing". Vertical bouncing occurs when the pilot involuntarily provides collective input while being accelerated in vertical direction. Depending on the phase relationships between acceleration and control input, related main rotor thrust changes might reinforce this motion pattern.

4.1 Representation of 'Aero-elastic RPC' Feedback Systems

From a control point of view, the vertical bouncing feedback can be approximated as follows:

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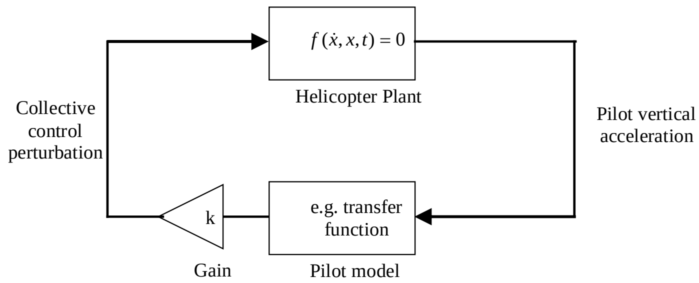

Figure 8: Closed loop system representing simplified 'aero-elastic RPC'

Main components of this feedback system are:

- a helicopter plant model representing rigid body degrees of freedom for the rotorcraft in flight, elastic airframe characteristics affecting pilot accelerations in addition and a main rotor model reflecting rotor dynamics while disturbed
- a pilot model representing collective control changes in dependency of seat accelerations by considering human body resonance characteristics
- a scalar feedback gain for conversion of collective grip motions to blade pitch changes and adjustment of units and signs

One typical approach in aero-elasticity to address such kind of problems is to use linearized representations assuming small motions during the on-set of the problem. An eigenvalue analysis of the linearized closed loop system matrix allows the determination whether the RPC system is predicted to be stable (only negative real parts of the system eigenvalues) or to be instable (at least one positive real part of the system eigenvalues). An alternative but more computational expensive approach is to perform time integration of the closed loop system equations and to monitor state or sensor amplitudes after an artificial initial disturbance.

4.2 Rotorcraft Plant Modeling

In order to represent the rotorcraft behavior adequately in the higher frequency range, complexity in terms of number of states needs to be increased drastically e.g. by elastic airframe and rotor modes compared to the 12x12 state models of the BO105 database. This rotorcraft model evolution results in the shift from analytical modeling i.e. by system equations set-up in a symbolic style manually or by computer algebra to numerical modeling using comprehensive rotor codes loosing traceability of the underlying physical parameters in the resulting system of equations. For illustration a typical model used at the beginning of the action group consisted of the following 72 states:

- Nine rigid body states of the helicopter (translations: first order; rotations: second order)
- Three main rotor dynamic inflow states (collective, lateral, longitudinal: all first order)
- Four elastic airframe states: two elastic airframe modes
- 14 elastic states per main rotor blade: seven elastic blade modes

With the progress of the technical activities of the action group, this model was consolidated e.g. by performing convergence studies allowing to reduce the number of states only slightly to 60 for the investigated phenomenon of vertical bouncing. Nevertheless – depending on the specific RPC problem to be investigated – additional components with dynamic impact might need to be considered as well in plant modeling such as actuator dynamics, flight control system and drive train and engine control system modes. Figure 9 and Figure 10 show dynamic characteristics derived from the baseline model. In order to embed the rotorcraft model into the RPC framework, system inputs and outputs are required as well for the related SISO system. As interfaces rotorcraft primary control reduced to collective control is selected as input and pilot accelerations (e.g. foot, seat, backrest) in terms of vertical accelerations on the floor group close to the seat location of pilot and co-pilot respectively are used as output.

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4.3 'Passive' Pilot Modeling

The considered frequency range for 'aero-elastic RPC' does no longer allow coordinated inputs from human beings; instead the pilot reacts more or less passively being externally disturbed. Thus, pilot models are totally different and, in a first approach, no longer mission task oriented. Again, modeling the pilot is a quite difficult task due to the large variability of human beings, due to pronounced non-linearity e.g. by pilot attitudes and due to variability of cockpit layouts and gains of control elements. A conventional approach to set up a pilot model is to measure the control displacements when the pilot is exposed to known vibrations, typically performed under laboratory conditions i.e. the pilot is put on a shaker table where a representative control system is installed in order to derive transfer functions based on the measurements. Inherently, the transfer functions and thus the pilot model are strongly linked to the geometric arrangements and dynamic properties of the controls in the test environment. Therefore, it is usually not possible to extrapolate the pilot models to different cockpits and control layouts imposing very strong limitations for this approach.

One of the best suited pilot models was presented by John R: Mayo, see [16]. Here, pilot transfer functions were measured using a classification into ectomorphic and mesomorphic subjects taking into account non-uniformity of human beings. Mayo identified a significant trend of the response magnitude with respect to the limb geometry. The transfer functions used in this action group were derived for the low stick region i.e. high gains. Typically, a lumped torso/limb/stick resonance is obtained in the 3 Hz to 4 Hz range, see Table 2. Figure 11 shows processing of the pilot model in order to get collective displacements when exposed to vertical accelerations.

The usage of the Mayo model is complemented in the action group by the application of the UoL motion based simulator for assessment of pilot model results in view of experimental set-ups. In order to overcome the limitations by the transfer function model as pure black box approach additional activities were launched by POLIMI implementing a multi-body system based model of relevant parts of the human body in view of vertical bouncing, see [6].

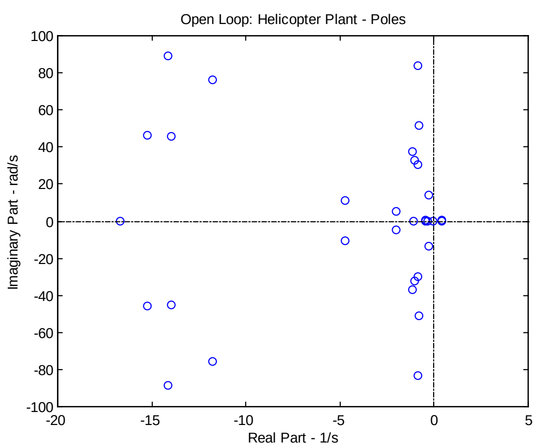

Figure 9: Zoomed pole map of the rotorcraft model: open loop in hover

Figure 10: Rotorcraft transfer function in hover for the pilot seat location

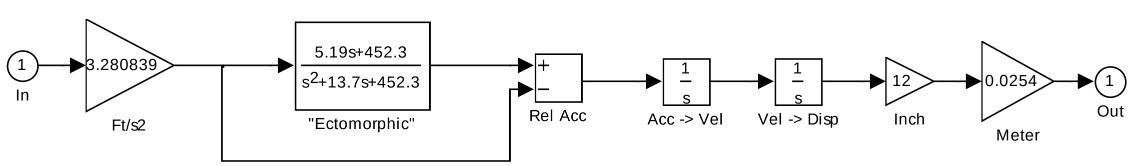

Figure 11: Ectomorphic pilot transfer function
Input vertical acceleration / Output collective displacement

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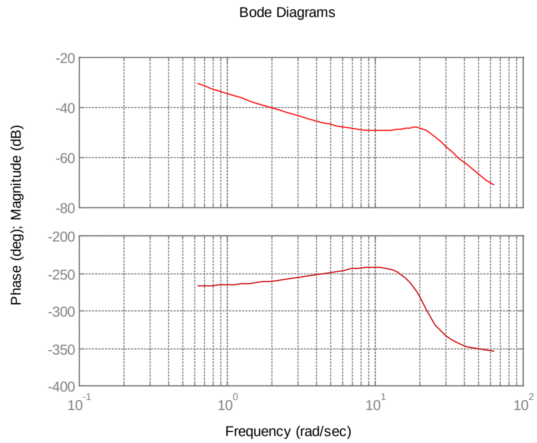

Figure 12: Bode diagrams of the ectomorphic pilot transfer function

	Frequency	Critical damping	„Undamped Frequency“
Ectomorphic pilot	3.2044 Hz	32.2%	3.3664 Hz
Mesomorphic pilot	3.5981 Hz	28.2%	3.7384 Hz

Table 3: Mayo pilot models for vertical bouncing

4.4 Baseline Results While "Closing the Loop"

Next, rotorcraft and pilot model were coupled by a feedback gain which can be understood as variable gain between travel of the collective grip and collective blade pitch. Please note that this approach is not consistent to the BO105 mechanical control design[4] but is used to produce a root locus of the closed loop system by sweeping from K=0 – open loop corresponding to pilot hands-off– to K=1 – closed loop. The BO105 database is intended to serve as numerical test bed as the BO105 is known to be RPC free. Furthermore, the pilot models do not account for the BO105 cockpit geometry. Thus, complete validation is not possible but results can be checked with respect to verification and for consistency.

In Figure 13, open loop is represented by blue circles while the closed loop case with nominal gain is marked with red symbols. For the hover case in combination with the ectomorphic pilot, almost indifferent stability is obtained for the coupled model poles with pilot contributions at nominal gain[5]. Thus, the analysis demonstrates destabilization of the coupled system by the pilot in the loop as expected. Next steps consisted in the analysis of variations such as operating conditions, co-pilot versus pilot, etc. E.g. Figure 14 demonstrates the impact of flight speed leading to instability for nominal gain setting. The destabilization by fast forward flight can be explained by the increased authority of the main rotor due to increased mean dynamic pressure acting on the rotor blades.

4.5 Performed Work and Conclusions on Aeroelastic RPC

Basic activities in the action group such as baseline 'aero-elastic RPC' cases overlapped between partners' work for verification purposes. Furthermore, the partners investigated special issues in a complementary manner for increased synergy:

- AHD: Performance of convergence and sensitivity studies of the baseline model, extension to MIMO cases (feeding back all pilot main rotor control) and consideration of slung loads
- POLIMI Intensive activities on pilot models by refining the simple pilot transfer model presented here and launch of activities on multi-body pilot modeling for adverse RPC
- UROMA3: Focus on impact of main rotor aerodynamic and inflow modeling beyond lifting line theory and uniform inflow models by application of potential flow methodologies

In addition, it should be highlighted that the provision of the motion base simulator by UoL incubated the extensive use of the simulator in the 'aero-elastic RPC' framework for biodynamic pilot modeling and 'aero-elastic RPC' simulations not anticipated initially.

[4] ... asking for a specific value for K by the geometrical arrangement of mechanical controls of the BO105.
[5] ... allowing an easy assessment when being compared against other numerical test cases.

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The partners demonstrated that 'aero-elastic RPC' could be adequately accessed by numerical means. Although no validation of the numerical means was possible due to missing flight test cases showing 'aero-elastic RPC', the investigations were assessed as successful proof of concept in view of applied methodologies. Although the appearance of 'aero-elastic RPC' might be manifold as stated in the beginning, the required steps for analysis are assumed to be quite similar. In order to close the gap of missing validation, it turned out that motion base simulation can be a valuable asset replacing flight test data, see also the next section.

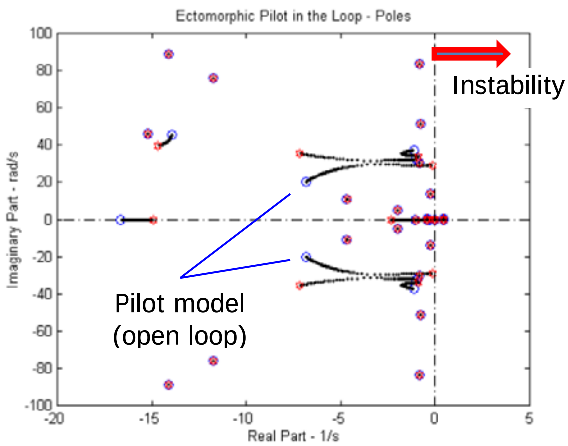

Figure 13: Closed loop system ectomorphic pilot: Hover case

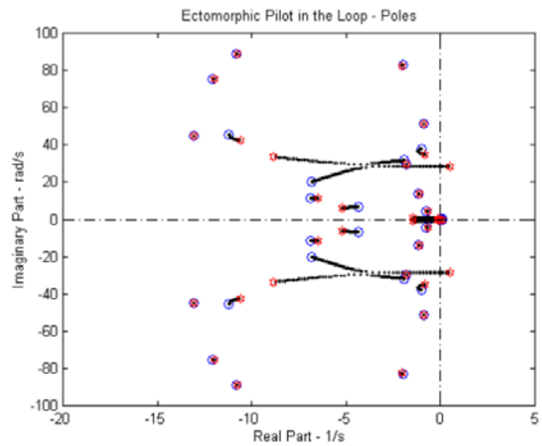

Figure 14: Closed loop system ectomorphic pilot: 150 KTAS, level flight[6]

5 RPC SIMULATOR TESTING

Beside the BO105 rotorcraft database, another highly valuable asset of the action group consisted in the accessibility to the University of Liverpool's motion base flight test simulator [7]. The standard usage of the simulator consisted in serving for 'rigid body RPC' demonstration which corresponds to the scope of conventional rotorcraft models based on flight dynamics. During the action group it turned out that the motion base simulator could beneficially serve as well for 'aero-elastic RPC' needs. The various test campaigns of the action group can be sorted as follows:

- 'Rigid body RPC' simulator tests: Closed loop operation incorporating flight mechanics rotorcraft models and pilot in the loop
- Biodynamic simulator tests: Feed forward operational mode for 'passive pilot system identification' including additional pilot instrumentation
- 'Aero-elastic RPC' simulator tests: Closed loop operation incorporating aero-elastic rotorcraft models and pilot in the loop

5.1 'Rigid Body RPC' Simulator Tests

The 'rigid body RPC' tests were designed to investigate the applicability of fixed wing RPC criteria to rotorcraft characteristics and to explore the boundaries defined by these criteria. Regarding simulator operation rotorcraft models in state space form were imported and not calculated intrinsically as usual. This approach offered advantages on the one hand by identical rotorcraft models for simulation and 'off-line' analysis easing cross-correlations. On the other hand, rotorcraft models with several modifications could be easily prepared and imported into the simulator e.g. allowing to fly different artificial flight control systems. The pilots were hereby asked to rate each "flown" configuration according to the PIO

[6] The numerical model does not account for power limits restraining v_H for the BO105 below 150 KTAS. For demonstration purposes of the analysis this discrepancy is accepted.

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rating (PIOR) scheme of Hess [17] which is analogue to the well-known Cooper-Harper Rating scale for handling qualities. Afterwards, the ratings were correlated with the predicted results.

To predict the BO105 model combinations which are RPC prone and RPC resistant using existing PIO criteria, a set of configurations were designed and set up to be implemented in the full-motion simulator of the University of Liverpool. 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 was given according to the PIO rating scale. After the tracking task was flown, the pilot had to concentrate on two manoeuvres as described in the ADS-33 handling qualities standard [13]: slalom and precision hover (see Figure 15). In ARISTOTEL [18], using extended simulator campaigns in the simulators in Liverpool and Delft, it was realized that the slalom maneuver should be replaced by a roll step maneuver which can trigger more easily RPCs in the simulator.

Figure 15 Manoeuvres flown to unmask RPC –University of Liverpool simulations [18]

5.2 Biodynamic Simulator Tests

The capability of the simulator to move the base including the entire cockpit was explicitly exploited by feeding pre-defined accelerations into the motion system and analyzing the response of the pilot with hands on controls in a biodynamic test campaign. One obvious advantage of this experimental approach is that the same test set-up including cockpit layout can be used on the one hand for investigating pilot's impedance and on the other hand for aeroelastic RPC tests hereby allowing cross-checks of pilot behavior.

Focus was put on the collective control loop in view of the analysis of the vertical bouncing phenomenon. In fact qualitative trends of the Mayo model could be confirmed although different shake test set-ups were used and the 'human test articles' used in the campaigns are expected to differ as well. For more details, the reader is referred to [6].

5.3 'Aero-elastic RPC' Simulator Tests

The simulation testing methodology for 'aeroelastic RPC' – initiated in the action group by using the simulator as shake table for passive pilot characteristics identification – was completed by closing the loop with an aero-elastic rotorcraft model. Thus two major issues had to be considered:

- Implementation of an elastic airframe model and the upgrade of the main rotor system by an elastic model with adequate degrees of freedom for covering the higher frequency range;
- For closure of the aeroelastic loop for vertical bouncing (and related) phenomena, modification of accelerations to be fed to the motion base by considering elastic motions of the airframe as well.

Please note that the accelerations provided to the motion base system of the simulator incorporate rigid body accelerations plus elastic accelerations experienced at the pilot seat. The assumption behind this approach was that the simulator itself is very stiff and the motions applied to the pilot seat in the

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simulator are the same as in the full scale helicopter featuring an elastic airframe. Figure 16 presents the control scheme behind this approach.
For demonstration purposes, a rotorcraft model including slung load was implemented into the simulator. The related flight simulation tests showed that the pilot can excite the slung load to oscillations by collective control inputs and that the pilot can adequately feel the slung load. Thus, suitability of the motion base simulator to treat 'aero-elastic RPC' phenomena was successfully proven.

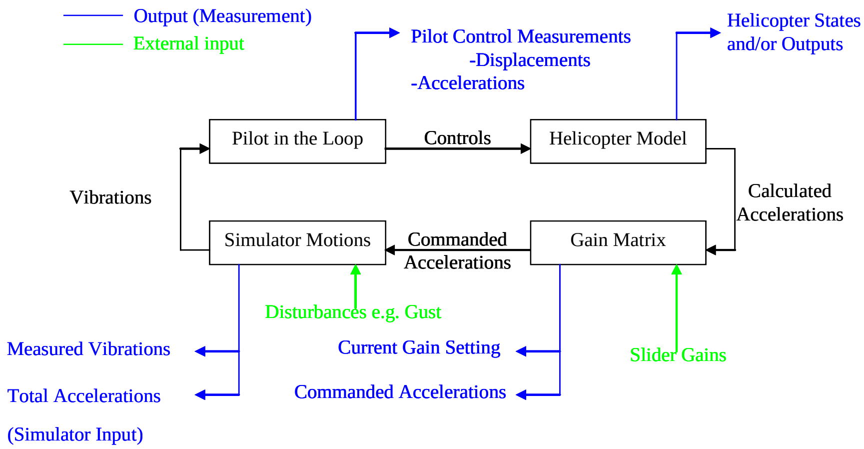

Figure 16: Motion base simulator test scheme for 'aero-elastic RPC'

5.4 Performed Work and Conclusions on RPC Simulator Testing

The intended role of the motion base simulator within this action group was significantly expanded by enabling the following synergetic aspects:

- Validation of fixed wing PIO analysis methods for rotorcrafts by enabling correlations with predictions of the PIO toolbox provided from 'fixed wing' action groups FM AG-12 and 15;
- Awareness and extensive information exchange of motion base simulator capabilities to 'aero-elastic RPC' group;
- Development of 'aero-elastic RPC' test methodology framework featuring the following two ingredients:
    - Biodynamic pilot identification and
    - Closed loop 'aero-elastic RPC' real-time simulations.

It is not known to the authors whether a similar approach in 'aero-elastic RPC' simulation was presented before in literature. The following partners proved to be major contributors in view of simulator activities:

- UoL: Operation of the simulator and satisfying 'strange requirements' especially from the 'aero-elastic RPC' partners;
- POLIMI: Support of biodynamic pilot testing e.g. preparing methods, provision of calibration hardware and pilot instrumentation using special sensors.

Unfortunately it turned out that the capabilities of the simulator serving the RPC studies could not be fully exploited in the action group – especially due to time constraints as the action group was limited in time and due to the time-consuming development process of 'aero-elastic RPC' test methods.

6 CONCLUSIONS

Extensive and collaborative work on rotorcraft pilot coupling was performed in the GARTEUR HC AG-16 action group by partners of five European nations. Several keys for success contributed to the wide-spread results of this action group. First of all, rotorcraft pilot coupling (RPC) as safety relevant topic

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allowed a thorough commitment to and identification with the corresponding research objectives. No segregate aspects had to be respected as it is usually the case in European rotorcraft research due to the strongly competitive market situation with two large rotorcraft manufacturers.

From technical point of view, the action group benefited significantly from research work performed by former action groups FM AG-12 and FM AG-15 in at least two aspects: First, provision of the PIO toolbox developed for fixed wing applications and now applied to the rotary wing world and second the personal identity of one of the participating partners involved in FM AG-12. Further valuable assets of the action group were the comprehensive database of the BO105 for modeling and the access to a motion base simulator for experimental testing. By addressing both 'rigid body RPC' and 'aero-elastic RPC' a beneficial technical exchange between these disciplines was favored by the focus on one rotorcraft (i.e. BO105) for both 'rigid body RPC' and 'aero-elastic RPC' and culminated in development of methods for using the simulator also for 'aero-elastic RPC' topics.

Nevertheless, it had to be accepted by the action group that the wide field of adverse rotorcraft pilot coupling cannot be fully treated by one single research project of this size. Thus, focus was also put on laying the foundations allowing to develop methodologies which can be applied to all relevant occurrences of rotorcraft pilot coupling. As natural consequence the action group has led to the set-up and performance of follow-on research projects on national and international level with the EU research project ARISTOTEL being the most prominent [9] featuring public workshops and more than 20 papers for dissemination e.g. [19].

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