Aircraft and Rotorcraft Pilot Couplings – Tools and Techniques for Alleviation and Detection

ACPO-GA-2010-266073

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Synthesis of publications from all contributing partners

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RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Document Information Table

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Executive Summary

This deliverable shows a summary of all publications issued within the project's lifetime by the partners. It also shows a synthesis of papers published in conference proceedings. The document is based on the entries the partners made in the Management Software "Project Angel" which is part of the project website and has been widely used since the start of the project.

Short project overview

The 3-year European research project ARISTOTEL focused on developing tools, techniques as well as design and simulation guidelines and methodologies for the prevention of aircraft-pilot couplings or rotorcraft-pilot couplings (A/RPC). These advanced technologies shall help in reducing the risk of accidents caused by these unfavourable phenomena. In order to start from a common base of understanding, the following revised definition of such couplings was established right at the start of the project:

"An Aircraft- or Rotorcraft-Pilot Coupling (A/RPC) is an unintentional (inadvertent) sustained or uncontrollable vehicle oscillations characterized by a mismatch between the pilot's mental model of the vehicle dynamics and the actual vehicle dynamics. The result is that the pilot's control input is out-of-phase with the response of the vehicle, possibly causing a diverging motion."

Introduction

The ARISTOTEL consortium produced several publications and articles for conference proceedings during the project's lifetime (01 October 2010 — 30 September 2013).

These ARISTOTEL publications are summarised in the present document. The deliverable has been set up under Work Package 6 — Dissemination and exploitation. Scientific publications of the ARISTOTEL consortium are submitted, approved by the other beneficiaries and archived in the internal part of the website, which is reserved for publications. Moreover, the publications are listed on the public project website and were regularly updated during project duration: Links to the publications were provided.

The present document is structured as follows:

- A statistical overview
- A synopsis of publications according to the research objectives of ARISTOTEL

A statistical overview

Altogether, 22 scientific publications and 35 conference papers have been and are being produced within the ARISTOTEL project. Several publications will also appear after the end of the project (see pages 26-34). The total number of publications is illustrated in the figure below.

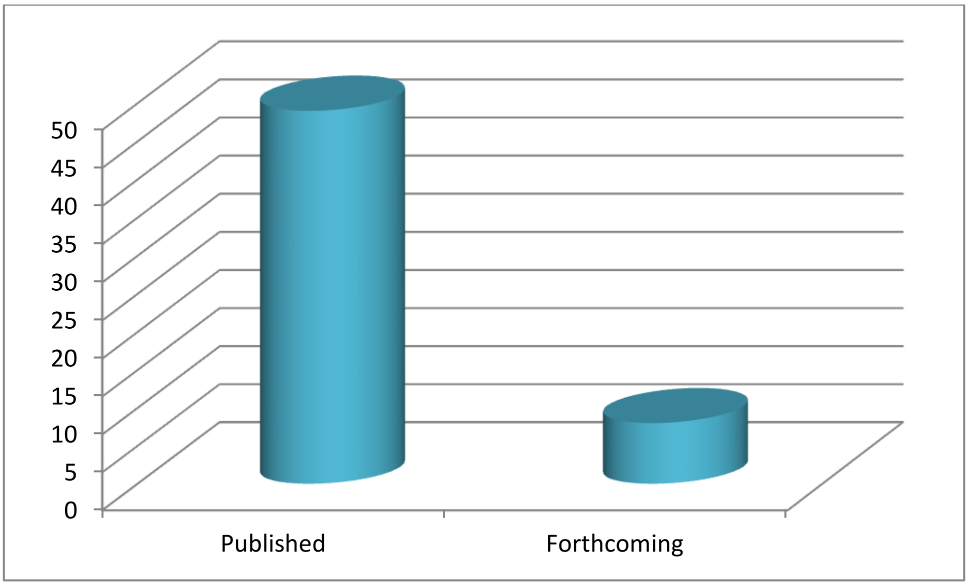


Figure 1: published vs forthcoming publications

Figure2: peer-reviewed articles vs. conference proceedings

In the following diagram, no differentiation is made as to how many beneficiaries have been involved in a joint publication.

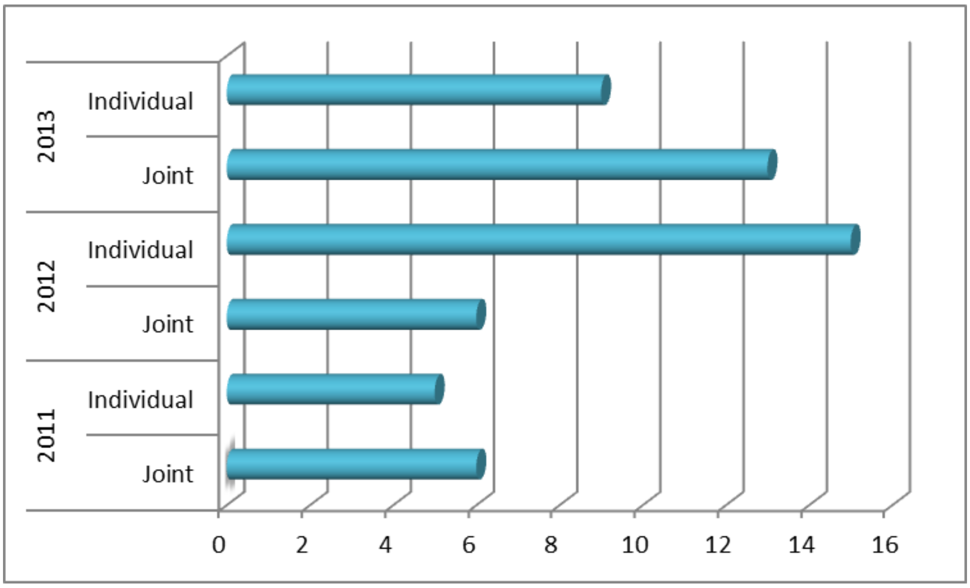


Figure 3: Year of publication; divided into joint and invidual

The articles/papers were published in the following journals:

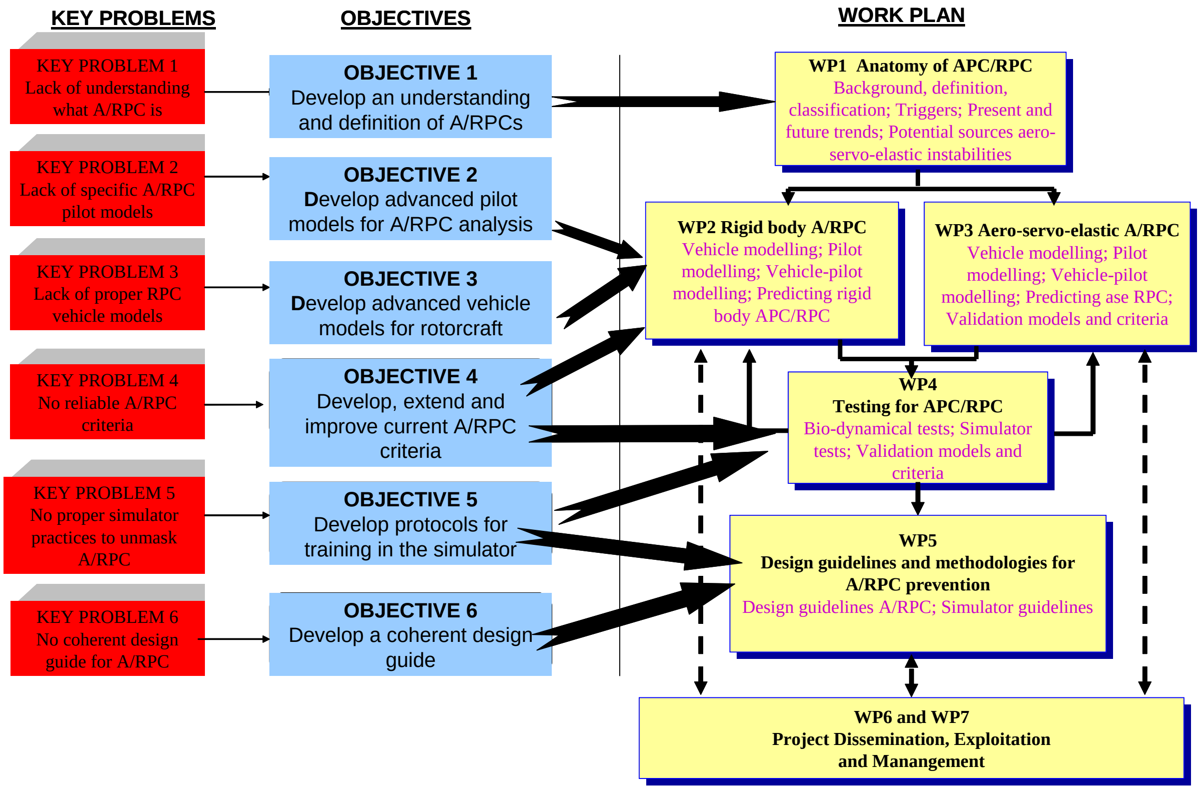
No.	Journal name	Audience	Impact factor	Comments
1	Aerotecnica, Missili e Spazio		n/a	
2	Journal of Aircraft		0,632	
3	The Aeronautical Journal		0,311	
4	INCAS BULLETIN		5.09	IC Value DOAJ
5	AIAA Journal of Guidance, Control and Dynamics		1.270	
6	Proceedings of the Institution of Mechanical Engineers, Part G, Journal of Aerospace Engineering		0.400	
8	Journal of Sound and Vibration		1.613	
9	CEAS Aeronautical Journal		n/a	
10	Journal of Multi-Body Dynamics		0.764	
11	Aerospace Science and Technology		0.873	

Furthermore, papers/articles were published in the following conference proceedings:

- 37th European Rotorcraft Forum 2011
- Aerodays 2011 Conference proceedings
- 68th AHS Forum Conference Proceedings
- IFASD 2011 Conference Proceedings
- CEAS 2011 conference proceedings

- XXII AIDAA Conference Proceedings
- IMSD 2012
- ASME IMECE 2012
- 69th AHS Forum
- ERF 2012
- ERF 2013

A synopsis of publications according to the ARISTOTEL research objectives



OBJECTIVE 1: Develop a general understanding on what an A/RPC is and how it manifests in existing and future aircraft and rotorcraft. Specifically, the proposed study will give a unified definition of A/RPC and its characteristic signature by:

- Exploring the background and current definitions and classifications of A/RPC
- Collecting a database of historic and recent A/RPC events that will provide a fundamental basis upon which A/RPC phenomena might be understood
- Defining future trends for A/RPC, based upon expected future vehicle design drivers. Among them are expected to be: the increasing bandwidth of flight control actuation systems, fly-by-wire and/or fly-by-light technologies.
- Understanding the various mechanisms related to aero-servo-elastic instabilities and their potential sources

A key consideration within this objective will be the prediction of the future trends for manifesting A/RPC in modern configurations and how they affect flight safety. Particular emphasis will be placed on the identification of the effects that advanced flight control systems may have on inducing A/RPC.

OBJECTIVE 2: A general framework for an advanced pilot model will be developed for A/RPC analysis including pilot neuromuscular system dynamics, the cockpit environment and the control chain including actuators. This framework must be capable of giving the FCS designer some indications of the level of detail needed in pilot modelling for analysing a specific A/RPC event. The project will give quantitative pilot behavioural models capable of revealing 1) what particular vibrations induce adverse effects in the pilot reaction and 2) how to mitigate these problems through the flight control system.

OBJECTIVE 3: A detailed framework for rotorcraft modelling will be created integrating rigid-body and aero-servo-elastic modelling features that can be interchanged according to the required accuracy and specific case considered. In this sense, the project will 1) advance the state-of-the-art presently used for modelling the rotorcraft specifically in RPCs and 2) understand the level of detail needed for modelling a RPC, either related to rigid-body motion or aero-servo-elastic analysis.

OBJECTIVE 4: The project will extend and improve the current criteria for predicting Cat. I, Cat. II and Cat. III A/RPCs and where possible define new criteria that better characterise the A/RPC-prone configurations. The new criteria will include the effect of vibrations on pilot control behaviour and will take into account the future trends of manifesting A/RPCs in modern configurations.

OBJECTIVE 5: Develop protocols (guidelines) for aircraft and rotorcraft pilot training in simulated and actual flight test sorties capable of unmasking adverse RPC tendencies. These protocols will be based on the benchmark of explicit tests that will be first defined in this project. The tests will involve mainly precise and aggressive manoeuvring mission tasks, inducing high vibratory loads on the airframe that couple via the FCS dynamics to the pilot's bio-dynamics. The resulting tests will maximize the use of flight simulator for A/RPC detection.

OBJECTIVE 6: Develop a coherent design guide that provides a disciplined and structured approach to be taken into the design process to avoid adverse A/RPCs. Within this context, the project aims to give the designer the flexibility to choose the design parameters of the configuration least exposed to RPCs.

Publications: Peer-Reviewed Articles

Title	**Robust aeroservoelastic analysis for the investigation of rotorcraft pilot couplings**
Objective(s)	Objective 4, Objective 6
Abstract	Aircraft-Pilot Couplings, namely the adverse interaction of the pilot with the aeromechanics of aircraft, are potentially dangerous phenomena. The prediction of aircraft proneness to this type of phenomena is usually difficult prior to flight testing. Their occurrence in rotorcraft, called Rotorcraft-Pilot Couplings, received less attention until recent years. Robust stability analysis techniques mutuated from robust control theory are used in this work to develop a simple and versatile method for the investigation of the boundaries of pilot biodynamic feedthrough that guarantees the stability of the coupled system no matter how complex the vehicle model is. The proposed method is applied to the analysis of a detailed model of a medium weight helicopter, and results are discussed.
Contact person	P.Masarati — e-mail: pierangelo.masarati@polimi.it
Authors	V. Muscarello, P. Masarati, G. Quaranta
Involved institution(s)	POLIMI
Publication date	March 2012
Reference	Aerotecnica, Missili e Spazio, Vol. 91, n. 1-2
DOI	

Title	**Multiblade Reduced-Order Aerodynamics for State-Space Aeroelastic Modeling of Rotors**
Objective(s)	
Abstract	Reduced-order aerodynamic models are tools that may be conveniently applied in a wide range of research and design applications in the aeronautical and mechanical fields. This paper presents a methodology for the identification of a Reduced-Order Model (ROM) describing the linearized unsteady aerodynamics of helicopter rotors in arbitrary steady flight, that is particularly suited for the derivation of the state-space perturbation aeroelastic operators and hence useful for stability analysis and aeroservoelastic applications. It is defined in terms of multiblade coordinates and yields a (finite-state) constant-coefficient, linear, differential form relating them to the corresponding multiblade aerodynamic loads. This approach requires the prediction of a set of harmonic perturbation responses by an aerodynamic solver. The accuracy of the identified ROM in describing unsteady aerodynamics phenomena is strictly connected to that of the aerodynamic solver. Complex aerodynamic effects (like wake roll up, wake-blade interactions) are included in the ROM if they are taken into account in evaluating the harmonic responses. Numerical results concerning a flap-lag helicopter rotor in forward flight are presented. These examine the accuracy the aerodynamic ROM introduced both in terms of aerodynamic loads predictions and in terms of aeroelastic stability analysis. An aeroservoelastic application is also included in order to demonstrate the suitability of the ROM proposed for the design of controllers.
Contact person	M. Gennaretti — e-mail: m.gennaretti@uniroma3.it
Authors	M. Gennaretti, D. Muro
Involved institution(s)	UROMA3
Publication date	April 2012
Reference	Journal of Aircraft, Vol. 49, No. 2
DOI	10.2514/1.C031422

Title	**An Optimal Control Approach for Alleviation of Tiltrotor Gust Response**
Objective(s)	Objective 3, Objective 4
Abstract	The alleviation of gusts effects on a tiltrotor in airplane and helicopter operation modes obtained by an optimal control methodology based on the actuation of elevators, wing flaperons and swashplate is examined. An optimal observer for state estimate is included in the compensator synthesis, with the Kalman-Bucy filter applied in the presence of stochastic noise. Tiltrotor dynamics is simulated through an aeroelastic model that couples rigid-body motion with wing and proprotor structural dynamics. An extensive numerical investigation examines effectiveness and robustness of the applied control procedure, taking into account the action of both deterministic and stochastic vertical gusts. In addition, a passive pilot model is included in the aeroelastic loop and the corresponding effects on uncontrolled and controlled gust response are analysed.
Contact person	M. Gennaretti — e-mail: m.gennaretti@uniroma3.it
Authors	M. Gennaretti, D. Muro, M. Molica Colella, J. Serafini
Involved institution(s)	UROMA3
Publication date	June 2012
Reference	Royal Aeronautical Society, Vol. 116, No. 1180
DOI	

Title	**Trigger event - a key factor in adverse Aircraft/Rotorcraft Pilot Couplings**	
Objective(s)	Objective 1	
Abstract	An important element that interacts unfavorably with pilot and aircraft is the triggering event. Without a trigger event (or a chain of triggering events) A/RPC does not appear. This study presents an overview of different classes of triggers that can initiate an A/RPC phenomenon. Based on extended analysis of triggering events a new definition is proposed.	
Contact person	A. Ionita	e-mail: achim.ionita@straero.ro
Authors	A. Ionita	
Involved institution(s)	STRAERO	
Publication date	October 2012	
Reference	INCAS BULLETIN, Vol. 4, No. 3	
DOI	ISSN 2066-8201	

Title	**Development of the Phase-Aggression Criterion for Rotorcraft Pilot Coupling Detection**
Objective(s)	
Abstract	Significant effort has been expended to develop criteria to predict the susceptibility of an air vehicle to socalled Pilot-Induced Oscillations (PIO). Much of this work has been carried out for fixed-wing aircraft and it is only recently that their applicability to rotorcraft has started to be assessed. Real-time PIO identification methods provide an alternative means to at least warn the pilot that a PIO is in progress so that preventative action can be taken. Existing methods, however, have some limitations and have rarely been used for rotarywing purposes. Specifically, the methods assessed in this paper do not provide an indication of the severity of the event and mask the underlying data that is being used to generate the warning. This paper proposes and presents a new method to identify PIOs, either in near real-time or as a post-processing aid for recorded flight test data that addresses both of these issues. The new method, entitled 'Phase-Aggression Criterion' is compared with existing current methods. It is shown, for a specific set of test cases that not only can it provide more information about the PIO but that it can also provide a small but significant earlier warning of its onset.
Contact person	M. Jones — e-mail: Michael.Jones@liverpool.ac.uk
Authors	M. Jones, M. Jump, L. Lu
Involved institution(s)	UoL
Publication date	January 2013
Reference	AIAA Journal of Guidance, Control and Dynamics, Vol. 36, No. 1
DOI	10.2514/1.58232

Title	**Tau Coupling Investigation Using Positive Wavelet Analysis**
Objective(s)	
Abstract	Investigation into motion guidance using tau (τ) theory primarily relies on the accurate calculation of the coupling term between the τ (time-to-contact) of the motion and its relevant tau guide. However, the traditional approach for this calculation can be numerically unstable, requires experience and skill to execute in a meaningful manner, is sensitive to the data segments selected, and has limited application when the motion information is incomplete. A new approach, based on positive wavelet analysis combined with the new concept of a guidance element, is proposed and validated in this paper to deal with these issues. The mother wavelet is constructed using the desired τ-guide shapes with its scale considered as the maneuver period. The scale and time information of interest are found by searching the best local correlation with the whitened original signal. An inverse de-whitening process is then used to reconstruct an approximation to the original motion signal. The adequacy of the proposed method has been demonstrated using data obtained from piloted simulation test campaigns. The results show that the proposed approach is not only feasible, but has better numerical stability, reliability, enhanced performance and potentially a wider application than the methods that have been used to date.
Contact person	L. Lu — e-mail: Linghai.Lu@liverpool.ac.uk
Authors	L. Lu, M. Jump, M. Jones
Involved institution(s)	UoL
Publication date	January 2013
Reference	AIAA, Journal of Guidance, Control, and Dynamics, Vol. 36, No. 4
DOI	10.2514/1.60015

Title	**Experimental and numerical helicopter pilot characterization for aeroelastic rotorcraft-pilot couplings analysis**
Objective(s)	Objective 2, Objective 5
Abstract	Pilot-vehicle interaction represents a critical aspect of aircraft design. Very low frequency, voluntary although unintentional interaction has been extensively investigated in fixed and rotary wing aeromechanics. Higher frequency, involuntary and thus passive interaction received similar attention in fixed wing aeromechanics, but not as much for rotary wing. This work presents the results of an experimental campaign focused on the characterization of the passive behavior of rotorcraft pilots' biomechanics. Human subjects were subjected to excitation spectra in a flight simulator, recording the accelerations of their limbs and the motion induced by the limbs' vibrations into the control inceptors. Independent excitations in the vertical, longitudinal and lateral directions have been considered. In the first case, measures were related to the motion of the collective lever and of the left arm, while in the last two cases they were related to the motion of the cyclic stick and of the right arm. The response has been evaluated, mainly in the frequency domain; resulting noteworthy behavior is discussed in view of its relevance in modeling the passive biomechanical behavior of pilots for coupled bio-aeroservoelastic analysis of rotorcraft. The measurements of human body impedance, under realistic cockpit motion, are used to identify the direct transfer function between the motion of the seat and the controls inadvertently fed back into the rotorcraft.
Contact person	P. Masarati — e-mail: pierangelo.masarati@polimi.it
Authors	P. Masarati, G. Quaranta, M. Jump
Involved institution(s)	POLIMI, UoL
Publication date	January 2013
Reference	Proceedings of the Institution of Mechanical Engineers, Part G, Journal of Aerospace Engineering, Vol. 227, No. 1
DOI	10.1177/0954410011427662

Title	**Analysis of a structural-aerodynamic fully coupled formulation for aeroelastic response of rotorcraft**
Objective(s)	
Abstract	This paper deals with a computational aeroelastic tool aimed at the analysis of the response of rotary wings in arbitrary steady motion. It has been developed by coupling a nonlinear beam model for blades structural dynamics with a potential-flow boundary integral equation solver for the prediction of unsteady aerodynamic loads around three- dimensional, lifting bodies. The Galerkin method is used for the spatial integration of the resulting differential aeroelastic system, whereas the periodic blade response is determined by a harmonic balance approach. This aeroelastic model yields a unified approach for aeroelastic response and blade pressure prediction, that may conveniently be used for aeroacoustic purposes. It is able to examine configurations where blade-vortex interactions occur. Numerical results show the capability of the aeroelastic tool to evaluate blade response and vibratory hub loads for a helicopter main rotor in level and descent flight conditions, and examine the efficiency and robustness of the different numerical solution algorithms that may be applied in the developed aeroelastic solver. Comparisons among aeroelastic predictions based on different aerodynamic models are also presented.
Contact person	G. Bernardini — e-mail: g.bernardini@uniroma3.it
Authors	G. Bernardini, J. Serafini, M. Molica Colella, M. Gennaretti
Involved institution(s)	UROMA3
Publication date	March 2013
Reference	Aerospace Science and Technology, Vol. 29, No. 1
DOI	10.1016/j.ast.2013.03.002

Title	**Rotorcraft Aeroelastic Stability Using Robust Analysis**
Objective(s)	Objective 3, Objective 4
Abstract	This paper discusses the impact of different models of aerodynamic loads on rotorcraft-pilot couplings stability using a robust stability analysis approach. The aeroelasticity of the main rotor of a helicopter is formulated using aerodynamic models based on blade element/momentum theory and boundary element method coupled to a finite element model of the blade. The resulting linearized models are used to determine stability limits according to the generalized Nyquist criterion, associated with the accelerations of the pilot's seat caused by the involuntary action of the pilot on the control inceptors. The resulting stability curves are discussed considering examples of involuntary pilot transfer functions from the literature.
Contact person	G. Quaranta — e-mail: guiseppe.quaranta@polimi.it
Authors	G. Quaranta, A. Tamer, V. Muscarello, P. Masarati, M. Gennaretti, J. Serafini, M. Molica Colella
Involved institution(s)	POLIMI, UROMA3
Publication date	July 2013
Reference	CEAS Aeronautical Journal
DOI	10.1007/s13272-013-0082-z

Title	**Dependence of helicopter pilots' biodynamic feedthrough on upper limbs' muscular activation patterns**
Objective(s)	Objective 2
Abstract	The involuntary interaction of pilots with vehicles is often an undesired consequence of the biodynamic feedthrough of cockpit vibrations into the control system in relation with the characteristics of the man-machine interface. This work presents a numerical study of how estimated muscular activation patterns associated to performing basic helicopter piloting tasks may affect the variability of the pilot's biodynamic feedthrough and admittance. The limbs' motion is predicted using an inverse kinematics formulation for redundant manipulators imposing the motion of the hand from measurements. Articulation torques are then estimated by inverse dynamics. Activation of the involved muscles is estimated according to the 'total activation' paradigm. Equivalent pilot feedthrough is obtained by consistent linearization of the constitutive model of the muscles about the reference activation. The effect on equivalent feedthrough of non-optimal activation, resulting from the addition of torque-less activation modes to the optimal activation, is evaluated and discussed. The multibody model of the pilot's biodynamic feedthrough is incorporated in a detailed multibody model of a helicopter, to perform coupled bioaeroservoelastic simulations.
Contact person	P. Masarati — e-mail: pierangelo.masarati@polimi.it
Authors	P. Masarati, G. Quaranta, A. Zanoni
Involved institution(s)	POLIMI
Publication date	July 2013
Reference	Journal of Multi-Body Dynamics
DOI	10.1177/1464419313490680

Title	**A Finite-State Aeroelastic Model for Rotorcraft-Pilot-Coupling Analysis**
Objective(s)	Objective 3, Objective 4, Objective 6
Abstract	Rotorcraft-pilot coupling (RPC) denotes interplay between pilot and helicopter (or tiltrotor), that may give rise to adverse phenomena. These are usually divided into two main classes: Pilot Induced Oscillations (PIO) driven by flight dynamics and behavioural processes, and Pilot Assisted Oscillations (PAO) caused by unintentional actions of pilot on controls, owing to involuntary reaction to seat vibrations. The aim of this paper is the development of mathematical helicopter models suited for analysis of RPC phenomena. In addition to rigid-body dynamics, RPCs are also related to fuselage structural dynamics and servoelasticity (especially PAO), but a crucial role is played by main rotor aeroelasticity. Here, the aeroelastic behaviour of the main rotor is simulated through a finite-state model that may conveniently be applied for rotorcraft stability and response analyses, as well as for control synthesis applications. Numerical results are focused on the validation of the proposed main rotor model, along with to the assessment of its sensitivity to the aerodynamic formulation applied within the aeroelastic operator. Further, considering a Bo-105-type helicopter, the comprehensive rotorcraft model is applied for the analysis of vertical bouncing, which is a PAO phenomenon caused by coupling of vertical pilot seat acceleration with collective control stick, driven by inadvertent pilot actions.
Contact person	J. Serafini — e-mail: serafini@uniroma3.it
Authors	J. Serafini, M. Molica Colella, M. Gennaretti
Involved institution(s)	UROMA3
Publication date	05 July 2013
Reference	CEAS Aeronautical Journal
DOI	10.1007/s13272-013-0086-8

Title	**A Practical Biodynamic Feedthrough Model for Helicopters**
Objective(s)	
Abstract	Biodynamic feedthrough (BDFT) occurs when vehicle accelerations feed through the pilot's body and cause involuntary motions of limbs, resulting in involuntary control inputs. BDFT can severely reduce ride comfort, control accuracy and, above all, safety during the operation of rotorcraft. Furthermore, BDFT can cause and sustain rotorcraft-pilot couplings. Despite many different studies conducted in past decades—both within and outside of the rotorcraft community—BDFT is still a poorly understood phenomenon. The complexities involved in BDFT have kept researchers and manufacturers in the rotorcraft domain from developing robust ways of dealing with its effects. A practical BDFT pilot model, describing the amount of involuntary control inputs as a function of accelerations, could pave the way to account for adverse BDFT effects. In the current paper, such a model is proposed. Its structure is based on the model proposed by Mayo (15th European Rotorcraft Forum, Amsterdam, pp. 81-001–81-012 1989), and its accuracy and usability are improved by incorporating insights from recently obtained experimental data. An evaluation of the model performance shows that the model describes the measured data well and that it provides a considerable improvement to the original Mayo model. Furthermore, the results indicate that the neuromuscular dynamics have an important influence on the BDFT model parameters.
Contact person	M. Pavel — e-mail: M.D.Pavel@tudelft.nl
Authors	J. Venrooij, M. Pavel, M. Mulder, .F. van der Helm, H. Bülthoff
Involved institution(s)	TUD
Publication date	05 July 2013
Reference	CEAS Aeronautical Journal
DOI	10.1007/s13272-013-0083-y

Title	**Impact of Pilots' Biodynamic Feedthrough on Rotorcraft by Robust Stability**
Objective(s)	Objective 2, Objective 4, Objective 6
Abstract	The coupling of rotorcraft dynamics with the dynamics of one of the main system devoted to its control, i.e. the pilot, may sometimes lead to several peculiar phenomena, denominated Rotorcraft Pilot Couplings (RPC), all characterized by an abnormal behavior that may endanger the safety of flight. Among them, there is a special class of couplings which is dominated by the biodynamic behavior of the pilot's limbs that close the loop between the vibrations and the control inceptors in the cockpit. Leveraging robust stability analysis, the inherently uncertain pilot biodynamics can be treated as the uncertain portion of a feedback system, allowing analytical, numerical or graphical determination of proneness to RPC by comparing robust stability margins of helicopter models with experimental Biodynamic Feedthrough (BDFT) data. The application of the proposed approach to collective bounce is exemplified using simple analytical helicopter and pilot models and is applied to detailed helicopter models and experimental BDFT measurement data.
Contact person	G. Quaranta — e-mail: guiseppe.quaranta@polimi.it
Authors	G. Quaranta, P. Masarati, J. Venrooij
Involved institution(s)	POLIMI, TUD
Publication date	September 2013
Reference	Journal of Sound and Vibration
DOI	10.1016/j.jsv.2013.04.020

Title	**Adverse Rotorcraft Pilot Couplings – Past, present and future challenges**
Objective(s)	Objectives 1 to 6
Abstract	Fixed and rotary wing pilots alike are familiar with potential instabilities or with annoying limit cycle oscillations that arise from the effort of controlling aircraft with high response actuation systems. Understanding, predicting and suppressing these inadvertent and sustained aircraft oscillations, known as aircraft (rotorcraft)-pilot couplings (A/RPCs) is a challenging problem for the designers. The goal of the present paper is to give an overview on the state-of-the-art in RPC problem, underlining the future challenges in this field. It is shown that, exactly as in the case of fixed wing APCs, RPCs existed from the beginning of rotorcraft development and that the problem of eliminating them is not yet solved: the current rotorcraft modelling for RPC analysis is rather limited to the particular case analysed and there is a lack of quantitative pilot behavioural models to analyse RPCs. The paper underlines the importance of involuntary pilot control actions, generally attributed to biodynamic couplings in predicting RPCs in rotorcraft. It is also shown that recent experiences demonstrate that modern rotorcraft seem to embed tendencies predisposing the flight control system FCS system towards dangerous RPCs. As the level of automation is likely to increase in future designs, extending to smaller aircraft and to different kinds of operation, the consequences of the pilot 'fighting' the FCS system and inducing A/RPCs needs to be eradicated. In Europe, the ARISTOTEL project (2010–2013) has been launched with the aim of understanding and predicting modern aircraft's susceptibility to A/RPC. The present paper gives an overview of future challenges to be solved for RPC-free design and some new solutions herein
Contact person	M. Pavel — e-mail: M.D.Pavel@tudelft.nl
Authors	M. Jump, B. Dang Vu, P. Masarati, M. Gennaretti, A. Ionita, L. Zaichik, H. Smaili, G. Quaranta, D. Yilmaz, M. Jones, J. Serafini, J. Malecki
Involved institution(s)	All ARISTOTEL partners
Publication date	October 2013
Reference	Progress in Aerospace Sciences, Volume 62
DOI	10.1016/j.paerosci.2013.04.003

Publications: Forthcoming Peer-Reviewed Articles

Title	**Effects of Biodynamic Feedthrough in Rotorcraft-Pilot Coupling: the Collective Bounce-Case**
Objective(s)	Objective 3
Abstract	This paper discusses the aeroelastic interaction between helicopter and pilot called collective bounce. The problem is mostly studied in the time domain, using the multibody system dynamics approach to model the dynamics of the vehicle and the aeroelasticity of the main rotor, and a linear or quasi-linear transfer function approach for the voluntary and involuntary dynamics of the pilot. Different models are considered for the aerodynamic forces acting on the rotor, ranging from blade element/momentum theory to a boundary element method used independently and in co-simulation with the multibody model. The problem is analyzed in hover and forward flight, highlighting modeling requirements and the sensitivity of the stability results to a variety of parameters of the problem.
Contact person	M. Gennaretti — e-mail: m.gennaretti@uniroma3.it
Authors	M. Gennaretti, J. Serafini, P. Masarati, G. Quaranta
Involved institution(s)	POLIMI, UROMA3
Publication date	2013
Reference	AIAA, Journal of Guidance, Control, and Dynamics
DOI	10.2514/1.61355

Title	**The Role of Rotor Coning in Helicopter Proneness to Collective Bounce**
Objective(s)	Objective 1, Objective 4, Objective 6
Abstract	Collective bounce is a Rotorcraft Pilot Coupling (RPC) phenomenon caused by vertical vibrations in the aircraft cockpit that are transmitted to the collective lever through the torso, the left arm and the hand of the pilot, and fed back to the rotor through the collective pitch control. This paper shows how the occurrence of collective bounce is rooted in the coupling of the pilot biodynamics with the rotor cone mode. The damping of the cone mode, usually large, introduces significant phase delay. When coupled in feedback with the damped pilot biodynamics, this delay may lead to marginal stability conditions or even to instability. Simple analytical models are used to explain the basic mechanism of this coupling. Subsequent analyses also based on detailed helicopter models investigate the influence of several design parameters, and possible means of prevention are discussed.
Contact person	P. Masarati — e-mail: pierangelo.masarati@polimi.it
Authors	V. Muscarello, G. Quaranta, P. Masarati
Involved institution(s)	POLIMI
Publication date	2013
Reference	Submitted (to Aerospace Science and Technology)
DOI	n/a

ARISTOTEL

Title	**A Closed Loop Collective Bounce Adverse Aeroelastic Rotorcraft-Pilot Coupling Experiment**
Objective(s)	Objective 1, Objective 5
Abstract	This paper presents and discusses the results of a study focused on the biomechanical behavior of human subjects holding the collective control inceptor in a flight simulator. The reported experimental campaign was conducted at the HELIFLIGHT simulation facility of the University of Liverpool as part of the European Community sponsored project ARISTOTEL. The flight simulation model's motion was restricted to only the heave axis but was augmented to include an elastic mode of vibration in addition to the rigid heave mode. It is this augmentation that represents an element of novelty in the investigation. Four different pilots flew a number of alternative model configurations whose structural parameters had been varied. The placement of structural modes with a frequency of approximately 3.5 Hz resulted in observable unstable pilot-vehicle interactions. It was found that the presence of collective friction alleviates but does not completely eliminate this phenomenon. The models used for the study were very simple representations of reality. As such, the scalability of the results to numerical models representative of the structural dynamics of flexible helicopter airframes is also discussed.
Contact person	P. Masarati — e-mail: pierangelo.masarati@polimi.it
Authors	P. Masarati, G. Quaranta, L. Lu, M. Jump
Involved institution(s)	POLIMI, UoL
Publication date	2013
Reference	Journal of Sound and Vibration
DOI	10.1016/j.jsv.2013.09.020

FORTHCOMING PUBLICATIONS

Title	**A Multi-Loop Pilot Model for Boundary Triggered PIO Investigations**
Objective(s)	
Abstract	This paper presents the development of a multi-loop pilot model for use in Boundary-Triggered Pilot-Induced-Oscillation (PIO) investigations. In doing so, the Point Tracking (PT) and Boundary Avoidance (BA) elements of the pilot control strategy are assumed to act simultaneously for a PT-dominant task during a Boundary-Avoidance-Tracking (BAT) event. The theoretical analysis indicates that the essence of the BAT phenomenon consists of an additional requirement for the pilot to provide lead equalization as the boundary is approached as the task transitions from a full-attention PT task to both a PT and BA task. This process leads to a narrower open-loop system bandwidth and a larger tracking error, or the triggering of a PIO. It is also found that the severity of the BA influence can be reduced by including the effects of vestibular and proprioceptive cues into the model. The BAT pilot model exhibits pilot-vehicle responses that are consistent with those observed in a piloted-simulation study and can therefore be considered to be representative of pilot activity. Consideration of the results in the round indicates that the Boundary-triggered PIO can be categorized as Cat III PIO within the existing recognized taxonomy.
Contact person	L. Lu — e-mail: Linghai.Lu@liverpool.ac.uk
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Involved institution(s)	UoL
Publication date	2013
Reference	AIAA Journal of Guidance, Control, and Dynamics
DOI	n/a

Title	**Bioaeroservoelastic Analysis of Involuntary Rotorcraft-Pilot Interaction**
Objective(s)	Objective 2
Abstract	This work presents the integration of a detailed biomechanical model of the arms of a helicopter pilot and an equivalently detailed aeroservoelastic model of a helicopter, resulting in what has been called a 'bioaeroservoelastic' analysis. The purpose is to investigate potential adverse interactions, called rotorcraft-pilot couplings, between the aeroservoelastic system and the controls involuntarily introduced by the pilot into the control system in response to rotorcraft vibrations transmitted to the pilot through the cockpit, the so-called biodynamic feedthrough. The force exerted by the pilot on the controls results from the activation of the muscles of the arms according to specific patterns. The reference muscular activation value as a function of the prescribed action on the controls is computed using an inverse kinetostatics/inverse dynamics approach. A first-order quasisteady correction is adopted to mimic the reflexive contribution to muscle activation. Muscular activation is further augmented by activation patterns that produce elementary actions on the control inceptors. These muscular activation patterns, inferred using perturbation analysis, are applied to control the aircraft through the pilot's limbs. The resulting biomechanical pilot model is applied to the aeroservoelastic analysis of a helicopter model expressly developed within the same multibody modeling environment to investigate adverse rotorcraft pilot couplings. The model consists of the detailed aeroelastic model of the main rotor, using nonlinear beams and blade element/momentum theory aerodynamics, a component mode synthesis model of the airframe structural dynamics, and servoactuator dynamics. Results in terms of stability analysis of the coupled system are presented in comparison with analogous results obtained using biodynamic feedthrough transfer functions identified from experimental data.
Contact person	P. Masarati — e-mail: pierangelo.masarati@polimi.it
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Publication date	2013
Reference	ASME Journal of Computational and Nonlinear Dynamics
DOI	10.1115/1.4025354

FORTHCOMING PUBLICATIONS

Title	**Assessment of Analysis Criteria for PIO Susceptibility during Pitch-Axis Boundary-Avoidance-Tracking Manoeuvring**
Objective(s)	
Abstract	This paper reports on the assessment of a proposed set of optical-tau base criteria for the prediction of so-called Boundary Avoidance Tracking (BAT) events and Pilot-Induced Oscillation (PIO). The criteria had been developed during an initial investigation using in-flight and simulator test data for the roll-step boundary-tracking manoeuvre. This showed that pilots follow an optical tau-guide strategy during this manoeuvre and that potentially, the optical tau information could be usefully used to predict and analyse BAT phenomena. This paper extends the research by applying the developed criteria by using data from a rotary wing aircraft simulated flight BAT pitch axis experiment and assessing their validity. The investigation describes the experiment and shows that the proposed criteria are largely appropriate for the intended purpose. In particular, the criterion to predict a BAT PIO is shown to be valid. However, because the data does not cover the full extent of the criteria, further work will need to be conducted to fully validate them. The work presented also contributes by showing why the variables involved in the criteria are important and relevant. Both the first and second derivatives of optical tau are shown to be surrogates for the pilot's control activity in the axis considered.
Contact person	L. Lu — e-mail: Linghai.Lu@liverpool.ac.uk
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Involved institution(s)	UoL
Publication date	2013
Reference	Journal of Guidance, Control, and Dynamics
DOI	n/a

ARISTOTEL

Title	**Flight Simulator Investigations of Adverse Aeroservoelastic Roll Rotorcraft-Pilot Coupling**
Objective(s)	Objective 1, Objective 5
Abstract	This paper presents the results of a flight simulator test campaign aimed at understanding the effect of high-frequency dynamics associated with helicopter aeroservoelasticity on the proneness to rotorcraftpilot couplings and specifically to pilot-assisted oscillations. Linearised aeroservoelastic models representative of helicopters in hover and in forward flight have been flown in a full motion flight simulator by trained test pilots, performing selected mission task elements. The handling qualities of the vehicles have been intentionally degraded by modifying the gearing ratios between the control inceptors and the flight controls and by introducing time delays representative of realistic fly-by-wire flight control systems. Clear evidence of pilot-induced oscillations has been found while performing the roll step manoeuvre, especially with the soft-inplane hingeless helicopter with a lightly damped main rotor first regressive lead-lag mode. Based on subjective pilot ratings and objective measures, the aeroservoelastic models require higher pilot workload than corresponding rigid-body models. The repeatable occurrence of an unstable pilot-assisted oscillation event with only one test pilot flying the aeroservoelastic model has been explained by the interaction of the pilot's involuntary biodynamic feedthrough, identified by specific experiments, and the above mentioned regressive lead-lag mode.
Contact person	P. Masarati — e-mail: pierangelo.masarati@polimi.it
Authors	P. Masarati, G. Quaranta, LL. Lu, M. Jones, M. Jump
Involved institution(s)	POLIMI, UoL
Publication date	n/a (planned publication)
Reference	AIAA Journal of Guidance, Control, and Dynamics
DOI	n/a

FORTHCOMING PUBLICATIONS

Title	**A multibody model for piloted helicopter flight dynamics and aeroservoelasticity**
Objective(s)	Objective 2, Objective 4
Abstract	This work presents the integration of a detailed multibody aeroservoelastic model of a helicopter with an equivalently detailed multibody model of the pilot arm biomechanics. The model is used to investigate the aeromechanics of the coupled system, including aeroelasticity and flight mechanics, with special focus on adverse rotorcraft-pilot couplings. The voluntary pilot control action required to fulfill specific tasks, produced according to state of the art paradigms, is fed into the control system by acting on the muscular activation required of the pilot limbs to move the control inceptors as needed for the maneuver. The integrated model is applied to the simulation of simple, yet representative mission task elements.
Contact person	P. Masarati — e-mail: pierangelo.masarati@polimi.it
Authors	G. Quaranta, G. Guglieri, A. Bernardini
Involved institution(s)	POLIMI
Publication date	2014 (planned publication)
Reference	ASME Journal of Computational and Nonlinear Dynamics
DOI	n/a

Conference proceedings

Title	**Measuring biodynamic feedthrough in helicopters**
Objective(s)	
Abstract	Biodynamic feedthrough (BDFT) refers to a phenomenon where vehicle accelerations cause involuntary pilot limb motions which, when coupled to a control device, can result in unintentional control inputs. It is known that BDFT occurs in helicopters, amongst many other vehicles. The goal of the current study is to analyze the pilot's response to helicopter motion and experimentally determine the level of BDFT occurring in helicopters. In this study, BDFT was measured for the collective and the cyclic control devices, in roll, pitch, and vertical direction, for three different control tasks, a position task (PT) or 'stiff task', a force task (FT) or 'compliant task', and a relax task (RT). The study focuses on the influence of the pilot's neuromuscular dynamics on the level of BDFT. Two major conclusions can be drawn from the experimental results: 1) BDFT in helicopters is task dependent 2) the highest level of BDFT is measured in lateral direction, followed by longitudinal and finally vertical direction.
Contact person	M. Pavel — e-mail: M.D.Pavel@tudelft.nl
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Publication date	2011
Reference	37th European Rotorcraft Forum Proceedings
DOI	ISBN: 978-1-61839-626-6

Title	**Robust Aeroservoelastic Analysis for the Investigation of Rotorcraft Pilot Couplings**
Objective(s)	Objective 4, Objective 6
Abstract	Aircraft-Pilot Couplings, namely the adverse in- teraction of the pilot with the aeromechanics of aircraft, represent a dangerous problem. The de- tection of an aircraft's proneness to this type of phenomenon is usually difficult prior to flight testing. Their occurrence in rotorcraft, called Rotorcraft-Pilot Couplings, has received less at- tention until recent years. This work applies ro- bust stability analysis techniques, mutuated from robust control theory, to develop a simple and versatile technique that allows to investigate the boundaries of the pilot's transfer function that guarantee the stability of the coupled system re- gardless of the complexity of the vehicle model. The proposed method is applied to the analysis of a detailed model of a medium weight helicopter, and the results are discussed.
Contact person	P.Masarati — e-mail: pierangelo.masarati@polimi.it
Authors	V. Muscarello, P. Masarati, G. Quaranta
Involved institution(s)	POLIMI
Publication date	2011
Reference	3rd CEAS Air&Space Conference Proceedings
DOI	ISBN 978-88-96427-42-2

Title	**Aircraft and Rotorcraft Pilot Coupling: a survey of recent research activities within the European project ARISTOTEL**
Objective(s)	
Abstract	Fixed and rotary wing pilots alike are familiar with potential instabilities or with annoying limit cycle oscillations that arise from the effort of controlling aircraft with high response actuation systems. Understanding, predicting and suppressing these inadvertent and sustained aircraft oscillations, respectively known as Aircraft- and Rotorcraft-Pilot Couplings (A/RPCs), is a challenging problem for the designers. Recent experiences show that especially modern designs are being confronted with an increasing degree of dangerous A/RPCs. The reason is that modern aircraft feature a significant level of automation in their Flight Control System (FCS). The FCS is generally intended to relieve pilot workload and allow operations in degraded weather and visibility conditions. Especially in modern rotorcraft, there seem to be embedded tendencies predisposing the FCS system towards triggering and sustaining dangerous RPCs. As the level of automation is likely to increase in future designs, extending to smaller aircraft and to different kinds of operation, the consequences of the pilot 'fighting' the FCS system and inducing A/RPCs needs to be eradicated. In Europe, the ARISTOTEL project (2010–2013) has been launched with the aim of understanding and predicting modern aircraft's susceptibility to A/RPC. The present paper gives an overview of the current status in RPCs and what can be expected in future designs.
Contact person	M. Pavel — e-mail: M.D.Pavel@tudelft.nl
Authors	M. Pavel, J. Malecki, B. DangVu, P. Masarati, G. Quaranta, M. Gennaretti, M. Jump, H. Smaili, A. Ionita, L. Zaicek
Involved institution(s)	TUD, PZL-Swidnik, ONERA, POLIMI, UROMA3, UoL, NLR, STRAERO, TsAGI
Publication date	October 2011
Reference	3rd CEAS Air&Space Conference Proceedings
DOI	ISBN 978-88-96427-42-2

CONFERENCE PROCEEDINGS

Title	**Aircraft and Rotorcraft Pilot Couplings – Tools and Techniques for Alleviation and Detection (ARISTOTEL)**
Objective(s)	
Abstract	Today's high performance aircraft are becoming more capable, faster and more complex than their predecessors. As their complexity increases, both engineers and pilots must deal with an associated increased incidence of unfavourable aircraft-and-rotorcraft pilot couplings (A/RPC). A/RPCs are undesirable and hazardous phenomena associated with pilot-aircraft interactions. They can range in severity from benign (affecting the mission operational effectiveness) to catastrophic (resulting in loss of aircraft and lives). Recently, the ARISTOTEL project (Aircraft and Rotorcraft Pilot Couplings – Tools and Techniques for Alleviation and Detection www.aristotel-project.eu) was launched within the 7th Framework Programme of the European Commission. The challenge of ARISTOTEL is to develop design tools and techniques needed to detect and alleviate the A/RPC problems. In the past, the key causal factor in A/RPCs appeared to be the pilot – this is why A/RPCs were usually known under the name of Pilot Induced Oscillations (PIOs). Recent experiences show that modern designs are being confronted in an increasing degree with dangerous A/RPCs. The reason for this is that modern aircraft feature a significant level of automation in their flight-control-systems (FCS). FCS is generally intended to relieve pilot workload and allow operations in degraded weather and visibility conditions. Especially in the modern rotorcraft, there seem to be embedded tendencies predisposing the FCS system towards dangerous RPCs. As the level of automation is likely to increase in future designs, extending to smaller aircraft and to different kinds of operation, the consequences of the pilot 'fighting' the FCS system and inducing A/RPCs needs to be eradicated. Based on an extended database of A/RPC events collected in the beginning of the project, A/RPCs were redefined according to their present and future trends. The next steps of the project will be to model properly the joint pilot-vehicle interactions and define prediction criteria for A/RPC analysis. Simulator and biodynamic tests (see Figure 1) will be used for validating these models and criteria. ARISTOTEL end products will be design and simulator guidelines for A/RPC detection.
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Publication date	2011
Reference	Aerodays 2011 Conference Proceedings

Title	**Fully Coupled Structural-Unsteady Aerodynamics Modelling for Aeroelastic Response of Rotorcraft**
Objective(s)	
Abstract	This paper deals with a computational aeroelastic tool for the analysis of rotorcraft. It has been developed by coupling a nonlinear beam model for blades (and wing) structural dynamics description with a boundary integral equation solver for the prediction of aerodynamic loads. This solver is based on three-dimensional, unsteady, potential aerodynamic formulation. The Galerkin method is used for the spatial integration, whereas the periodic blade (and wing) response is determined by a harmonic balance approach. This aeroelastic model yields a unified approach for aeroelastic response and blade pressure prediction that may conveniently be used for aeroacoustic purposes and, in addition, is able to examine configurations where blade-vortex interactions and multiple-body aerodynamic interactions occur. Numerical results show the capability of the aeroelastic tool to evaluate blade response and vibratory hub loads for a helicopter main rotor in level ight conditions, and examine the effciency and robustness of the different computational algorithms that might be applied in the presented aeroelastic solver. A sensitivity analysis of the predictions on the aerodynamics model used will be also discussed.
Contact person	G. Bernardini e-mail: g.bernardini@uniroma3.it
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Publication date	2011
Reference	37th European Rotorcraft Forum proceedings
DOI	ISBN 978-1-61839-626-6

CONFERENCE PROCEEDINGS

Title	**Stability Analysis of Helicopter Rotors in Forward Flight via State-Space Aeroelastic Modeling and Correlation with Experimental Results**
Objective(s)	
Abstract	Reduced-order aerodynamic models are tools that may be conveniently applied in a wide range of research and design applications in the aeronautical and mechanical fields. This paper presents aeroelastic applications of a Reduced-Order Model suited for the description of the linearized unsteady aerodynamics of helicopter rotors in arbitrary steady ight. It is defined in terms of multiblade coordinates and allows the derivation of statespace aeroelastic operators that are useful for stability analysis and aeroservoelastic applications. An aerodynamic solver has to be applied to get a set of harmonic responses from which the aerodynamic ROM is identified. In this paper, the state-space aeroelastic model of a four bladed hingeless soft-inplane helicopter main rotor in forward ight is derived, through harmonic solutions predicted by a potential-ow Boundary Element Method solver. It is applied to the analysis of the aeroelastic stability in several ight conditions, and the corresponding results are compared with experimental and numerical data available in the literature. These correlations validate the proposed procedure as suitable for the identification of state-space rotor aeroelastic models.
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Publication date	2011
Reference	37^{th} European Rotorcraft Forum Proceedings
DOI	ISBN 978-1-61839-626-6

Title	**An Investigation of Aeroelastic Rotorcraft-Pilot Interaction**
Objective(s)	Objective 3
Abstract	This paper presents the analysis of aeroelastic Rotorcraft-Pilot Coupling (RPC) problems. The structural dynamics of the airframe and of the rotor, and the dynamics of the control system, including the passive biomechanics of the pilot, are modeled using a free general-purpose multibody solver. The aerodynamics of the main rotor is modeled using an original free wake implementation based on the Boundary Element Method (BEM). The analysis is applied to the collective bounce problem, by assessing the existence of the phenomenon and the appropriateness of the aerodynamic and aeroservoelastic model for its analysis. The influence of various properties of the model on the stability of the response is discussed as well.
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Publication date	2011
Reference	37^{th} European Rotorcraft Forum Proceedings
DOI	ISBN: 978-1-61839-626-6

CONFERENCE PROCEEDINGS

Title	**Present and Future Trends in Rotorcraft Pilot Couplings (RPCs) – A Retrospective Survey of Recent Research Activities within the European project ARISTOTEL**
Objective(s)	
Abstract	Fixed and rotary wing pilots alike are familiar with potential instabilities or with annoying limit cycle oscillations that arise from the effort of controlling aircraft with high response actuation systems. Understanding, predicting and supressing these inadvertent and sustained aircraft oscillations, known as Aircraft (Rotorcraft)-Pilot Couplings (A/RPCs) is a challenging problem for the designers. Recent experiences show that especially modern designs are being confronted with an increasing degree of dangerous A/RPCs. The reason for this is that modern aircraft feature a significant level of automation in their Flight-Control-Systems (FCS). FCS is generally intended to relieve pilot workload and allow operations in degraded weather and visibility conditions. Especially in the modern rotorcraft, there seem to be embedded tendencies predisposing the FCS system towards dangerous RPCs. As the level of automation is likely to increase in future designs, extending to smaller aircraft and to different kinds of operation, the consequences of the pilot 'fighting' the FCS system and inducing A/RPCs needs to be eradicated. In Europe, the ARISTOTEL project (2010 – 2013) has been launched with the aim of understanding and predicting modern aircraft's susceptibility to A/RPC. The present paper gives an overview of the current status in RPCs and what can be expected in future designs.
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Publication date	2011
Reference	37th European Rotorcraft Forum Proceedings
DOI	ISBN: 978-1-61839-626-6

ARISTOTEL

Title	**Integrated Flight Dynamics and Aeroservoelasticity Modeling and Control of Tiltrotor Aircraft Using Multibody Simulation**
Objective(s)	Objective 3
Abstract	This work describes the application of an adaptive control algorithm based on Generalized Predictive Control to an aeroelastic model of a tiltrotor that includes rigid body degrees of freedom, restricted to the plane of symmetry. The model is augmented by an autopilot and a Stability Augmentation System; in some cases, a passive model of the biomechanics of the pilot is considered as well. The capability of the adaptive regulator to reduce loads and suppress flutter is assessed in different operating conditions.
Contact person	P. Masarati — e-mail: pierangelo.masarati@polimi.it
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Involved institution(s)	POLIMI
Publication date	2011
Reference	IFASD 2011 Conference Proceedings

CONFERENCE PROCEEDINGS

Title	**Aeroservoelastic Investigation of Rotorcraft-Pilot Coupling (RPC) by Coupled BEM/Multibody Analysis**
Objective(s)	Objective 3
Abstract	This paper presents a rotorcraft aeroservoelastic simulation analysis for the investigation of aeroelastic Rotorcraft-Pilot Coupling (RPC) problems. The structural dynamics of the airframe and of the rotor, and the dynamics of the control system, including the passive biomechanics of the pilot, are modeled using a free generalpurpose multibody solver. The aerodynamics of the main rotor is modeled using an original free wake implementation based on the Boundary Element Method (BEM). The analysis is applied to the collective bounce problem, by assessing the existence of the phenomenon and the appropriateness of the aerodynamic and aeroservoelastic model for its analysis.
Contact person	J. Serafini — e-mail: serafini@uniroma3.it
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Publication date	2011
Reference	IFASD 2011 Conference Proceedings

Title	**Multibody Analysis of Rotorcraft-Pilot Coupling**
Objective(s)	Objective 3
Abstract	This paper presents the multibody modeling of a complete aeromechanical model of a helicopter, compared to a corresponding, independently formulated linearized model, coupled to models of the voluntary and involuntary control exerted by the pilot on the collective control. The models are used to analyze the proneness of the helicopter to a characteristic instability called "collective bounce". The modeling approach is presented, with specific reference to those aspects of rotorcraft aeroservoelasticity and aeromechanics required to capture the phenomenon. The validation and the correlation of the models is presented and discussed. Rotorcraft-pilot coupling results related to stability are shown. The capability and effectiveness of the multibody analysis in simulating maneuvers is shown.
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Publication date	June 2012
Reference	2nd Joint International Conference on Multibody System Dynamics

Title	**Upper Limb Mechanical Impedance Variability Estimation by Inverse Dynamics and Torque-Less Activation Modes**
Objective(s)	Objective 2
Abstract	The involuntary interaction of the pilot with a vehicle is often an undesired consequence of the biomechanical properties of the human body and its relation with the layout of the man-machine interface. This work discusses how muscular activation patterns affect the variability of the equivalent impedance of helicopter pilots. A multibody model is used to compute the joint torques associated to a prescribed pilot task, which are then transformed into corresponding 'optimal' muscular activation patterns. Equivalent pilot impedance is obtained by consistently linearizing the constitutive model of the muscles about the reference activation. The effect on equivalent impedance of non-optimal activation, resulting from the addition of Torque-Less Activation Modes to the optimal activation, is evaluated and discussed.
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Involved institution(s)	POLIMI
Publication date	June 2012
Reference	2nd Joint International Conference on Multibody System Dynamics

Title	**Generic Research Simulator Requirements for Prediction of Adverse Rotorcraft Pilot Couplings in the Heave Axis**
Objective(s)	
Abstract	This paper presents the initial results of an investigation to study the effect of motion, visual and force-feel settings on incipience to Rotorcraft Pilot Couplings of a basic heave-only rotorcraft model within a generic rotorcraft flight simulator. Currently, there are no guidelines outlining requirements for simulation facilities to either validate offline Rotorcraft Pilot Coupling predictions or define new ones. The results indicate that it is important that simulation facilities be equipped with motion capabilities and correct force-feel characteristics. This is shown to be of greatest importance when assessing cases close to the boundaries of RPC incipience. The findings suggest that poor quality visual systems may be compensated for by the pilot through the use of any motion cueing available.
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Publication date	July 2012
Reference	68th AHS Annual Forum Conference Proceedings
DOI	ISBN: 9781622760510

CONFERENCE PROCEEDINGS

Title	**Theoretical and Experimental Investigation of Aeroelastic Rotorcraft-Pilot Coupling**
Objective(s)	Objective 1, Objective 5
Abstract	This paper presents and discusses the results of a study focused on the biomechanical behavior of human subjects holding the collective control inceptor in a flight simulator. The reported experimental campaign was conducted at the HELIFLIGHT simulation facility of the University of Liverpool as part of the EC sponsored project ARISTOTEL. The flight simulation model's motion was restricted to only the heave axis but was augmented to include an elastic mode of vibration in addition to the rigid heave mode. It is this augmentation that represents an element of novelty in the investigation. Four different pilots flew a number of alternative model configurations whose structural parameters had been varied. The placement of structural modes with a frequency of approximately 3.5 Hz resulted in observable unstable pilot-vehicle interactions. It was found that the presence of collective friction alleviates but does not completely eliminate this phenomenon. The models used for the study were very simple representations of reality. As such, the scalability of the results to numerical models representative of the structural dynamics of flexible helicopter airframes is also discussed.
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Publication date	July 2012
Reference	68th AHS Forum Conference Proceedings
DOI	ISBN: 978-1-62276-051-0

Title	**Robust Stability Analysis: A Tool to Assess the Impact of Biodynamic Feedthrough on Rotorcraft**
Objective(s)	Objective 2, Objective 4, Objective 6
Abstract	Biodynamic feedthrough (BDFT) may significantly affect the closed-loop behavior of rotorcraft, reducing the stability and increasing the proneness to Rotorcraft-Pilot Couplings (RPC). Leveraging robust stability analysis, the inherently uncertain pilot BDFT can be treated as the uncertain portion of a feedback system, allowing analytical, numerical or graphical determination of proneness to RPC by comparing robust stability margins of helicopter models with BDFT data. The application of the proposed approach to collective bounce is exemplified using simple analytical helicopter and pilot BDFT models and is applied to detailed helicopter models and BDFT measurement data.
Contact person	G. Quaranta — e-mail: quaranta@aero.polimi.it
Authors	G. Quaranta, P. Masarati, J. Venrooij
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Publication date	July 2012
Reference	68th AHS Forum Conference Proceedings
DOI	ISBN: 978-1-62276-051-0

CONFERENCE PROCEEDINGS

Title	**A Retrospective Survey of Adverse Rotorcraft Pilot Couplings in European Perspective**
Objective(s)	
Abstract	Fixed and rotary wing pilots alike are familiar with potential instabilities or with annoying limit cycle oscillations that arise from the effort of controlling aircraft with high response actuation systems. Understanding, predicting and suppressing these inadvertent and sustained aircraft oscillations, known as aircraft (rotorcraft)-pilot couplings (A/RPCs) is a challenging problem for the designers. The goal of the present paper is to give an overview on the state-of-the-art in RPC problem, underlining the future challenges in this field. It is shown that, exactly as in the case of fixed wing APCs, RPCs existed from the beginning of rotorcraft development and that the problem of eliminating them is not yet solved: the current rotorcraft modelling for RPC analysis is rather limited to the particular case analysed and there is a lack of quantitative pilot behavioural models to analyse RPCs. The paper underlines the importance of involuntary pilot control actions, generally attributed to biodynamic couplings in predicting RPCs in rotorcraft. It is also shown that recent experiences demonstrate that modern rotorcraft seem to embed tendencies predisposing the flight control system FCS system towards dangerous RPCs. As the level of automation is likely to increase in future designs, extending to smaller aircraft and to different kinds of operation, the consequences of the pilot ‘fighting’ the FCS system and inducing A/RPCs needs to be eradicated. In Europe, the ARISTOTEL project (2010–2013) has been launched with the aim of understanding and predicting modern aircraft's susceptibility to A/RPC. The present paper gives an overview of future challenges to be solved for RPC-free design and some new solutions herein.
Contact person	M. Pavel — e-mail: M.D.Pavel@tudelft.nl
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Publication date	2012
Reference	68th AHS Annual Forum Conference Proceedings
DOI	ISBN: 9781622760510

Title	**Identification of Pilot Control Behaviour during Rotorcraft-Pilot-Couplings**
Objective(s)	
Abstract	Rotorcraft Pilot Couplings (RPCs) - formerly called pilot induced/assisted oscillations" (PIO/PAO)- refer to inadvertent, sustained aircraft oscillations which are a consequence of an abnormal joint enterprise between the aircraft and the pilot [2]. In other words, RPC events are unexpected and annoying instabilities manifested as limit cycle oscillations that arise from pilot effort to control the aircraft. RPCs are typically triggered by a "mismatch" between the pilot and the vehicle dynamics and involve active pilot-induced oscillations (PIOs) and/or passive (piloted-assisted oscillations" (PAO"s)) participation of the pilot in the control loop. Despite decades of work to develop methods for their prevention, unfavourable aircraft/rotorcraft pilot couplings (A/RPCs) continue to occur. In 2010, the European Commission launched, under the umbrella of the 7th Framework Programme (FP7), the ARISTOTEL project (Aircraft and Rotorcraft Pilot Couplings – Tools and Techniques for Alleviation and Detection). The aim of this project is to advance the state-of-the-art of A/RPC prediction and suppression. With a duration of 3 years and involving partners from across Europe (for more information, see www.aristotel-project.eu), the ARISTOTEL project"s objectives are to improve the physical understanding of present and future A/RPCs and to define criteria to quantify an aircraft"s susceptibility to A/RPC. The goal of the present paper is to apply identification methods in order to understand pilot control behaviour in a RPC event. As task, the paper will concentrate on a hovering task where time delays are introduced in order to induce the RPC event. This is equivalent with triggering a Cat. I RPC event. Category I RPC are essentially linear and are caused directly by excessive time delays or phase lags in the vehicle dynamics. One should recall that, generally, according to the degree of non-linearity of the oscillation of the Pilot-Vehicle System (PVS), RPC are divided in four main categories: CAT I: Linear, CAT II: Quasi-Linear, CAT III: Nonlinear and CAT IV: Pilot Assisted Oscillations (PAO). Category II A/RPC"s are quasi-linear events and are triggered by the nonlinear rate and/or position limiting elements (RLEs and/or PLEs). Category III A/RPC"s are essentially non-linear PVS oscillations with transitions in command type of the Flight Control System (FCS) that cause a pilot mental mismatch. Category IV A/RPC"s are oscillations due to the coupling of elastic structural modes (aero elastic) and the pilot or due to biodynamical couplings.
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Involved institution(s)	TUD
Publication date	July 2012
Reference	38th European Rotorcraft Forum Proceedings

CONFERENCE PROCEEDINGS

Title	**Harmonizing the Realtime Oscillation verifier (Rover) with Handling Qualities Assessment for Enhanced Rotorcraft Pilot Couplings Detection**
Objective(s)	
Abstract	Aircraft and Rotorcraft Pilot Couplings (A/RPCs) – formerly called pilot induced/assisted oscillations" (PIO/PAO) – refer to inadvertent, sustained aircraft oscillations which are a consequence of an abnormal joint enterprise between the aircraft and the pilot. A/RPC problems are complex phenomena as they involve the pilot, the dynamics of the aircraft and a triggering factor. For present design configurations, it appears that APCs are associated with low frequency spectrum whereas RPCs may be associated with both low and high frequency spectra [ref. 1]. Vehicle A/RPC proness should be detected as early as possible in the design but, as this is difficult and cannot be guaranteed, it is logical to design a system capable to detect real-time any A/RPC danger and warn the pilot. In this way, the pilot can prevent the apparition of a fully developed RPC in real-time. The development of such a system started more than ten year ago. In this sense, for the detection of APC problems of fixed wing aircraft, a Real-time Oscillation Verifier (ROVER) concept was first developed for the U.S. Air Force. The principle of this concept consists in checking continuously in real-time the values of four aircraft parameters, i.e. the pitch rate, the longitudinal cyclic stick input, the phase delay between the two signals and finally the frequency of the pitch rate. The checks are done against certain threshold values of the above-enumerated parameters. Based on these checks, flags are issued. When four flags are gathered, an APC warning is displayed to the pilot.
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Publication date	July 2012
Reference	38th European Rotorcraft Forum Proceedings

Title	**Using the Phase-Agression Criterion to identify rotorcraft pilot coupling events**
Objective(s)	
Abstract	This paper describes the application of the newly developed Phase-Aggression Criterion to data obtained during a simulated flight test campaign, in order to assess its suitability to detect Rotorcraft Pilot Coupling events. Due to the increasing complexity of modern rotorcraft, both the frequency and severity of Rotorcraft Pilot Coupling events is envisaged to increase. This concern is also due to the lack of industry guidelines and standards when designing the 'future rotorcraft'. The Phase-Aggression Criterion is a detection tool for these events, capable of achieving a near real-time update of the vehicle's incipience to Rotorcraft Pilot Couplings. Boundaries used by the criteria serve to display severity of any detected 'events'. In this paper, the criterion has been applied to two Mission Task Elements, completed using four test pilots and two motion base simulators. The results presented illustrate good agreement between pilot subjective opinion, output test data and the Phase-Aggression boundary descriptors.
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Publication date	July 2012
Reference	38th European Rotorcraft Forum Proceedings

CONFERENCE PROCEEDINGS

Title	**Evaluation of Rotorcraft Aeroelastic Stability using robust analysis**
Objective(s)	Objective 3, Objective 6
Abstract	This paper discusses the impact of different aerodynamics models on rotorcraft-pilot couplings stability using a robust stability analysis approach. Models based on blade element/momentum theory and boundary element method, coupled to a finite element model of the blade, are used to formulate the aeroelasticity of the main rotor of a helicopter. The main rotor is coupled to a dynamic model of the airframe that also includes the dynamics of the control system. The resulting linearized models are used to determine stability limits according to the generalized Nyquist criterion, associated with the accelerations of the pilot's seat caused by the involuntary motion of the control inceptors. The resulting stability curves are discussed considering examples of involuntary pilot transfer functions from the literature.
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Authors	G. Quaranta, A. Tamer, V. Muscarello, P. Masarati, M. Gennaretti, J. Serafini, M. Molica Colella
Involved institution(s)	POLIMI, UROMA3
Publication date	July 2012
Reference	38^{th} European Rotorcraft Forum Proceedings

ARISTOTEL

Title	**Manoeuvring Rotorcraft Tau Coupling Investigation Using Positive Wavelet Analysis**
Objective(s)	
Abstract	The optical variable tau (τ), defined for an observer as some motion gap remaining to be closed divided by the instantaneous gap closure rate, provides a means of understanding the link between the world that a pilot sees through the cockpit window and the prospective control strategy that must be employed to guide a rotorcraft through the cluttered environment that is the Earth's surface. Tau theory has been intensively investigated in recent research efforts and much of this is conveniently summarised in Ref [1]. It is based on the premise that purposeful actions are accomplished by coupling the motion of the observer with either externally available or internally generated sources – the so-called motion guides [2]. When applied to flight control and handling qualities [1;3], it is hypothesized that the overall pilot's goal is to overlay or close the gap between the perceived optical flow-field and the required flight trajectory. The pilot then works directly with optical variables to achieve prospective control of the aircraft's future trajectory. One of the first applications to flight considered τ-guidance control strategies during helicopter deceleration manoeuvres close to the ground [4]. An investigation of terrain-hugging flight reinforced the prospective control behaviour of helicopter pilots [1]. Similar results have been found by applying τ-guidance to the landing flare manoeuvre of fixed-wing aircraft [3] and to boundary avoidance tracking in the roll-step manoeuvre [5] for rotorcraft. This paper extends the work to report on a method to improve the comparison between the vehicle's resultant motion and the appropriate tau-guide.
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Publication date	July 2012
Reference	38th European Rotorcraft Forum 2012

Title	**Effects of Manipulator Type and Feel System Characteristics on High-Frequency Biodynamic Pilot-Aircraft Interaction**
Objective(s)	
Abstract	Biodynamic feedthrough (BDFT) refers to a phenomenon where vehicle accelerations cause involuntary pilot limb motions which, when coupled to a control device, can result in unintentional control inputs. It is known that BDFT occurs in helicopters, amongst many other vehicles. The goal of the current study is to analyze the pilot's response to helicopter motion and experimentally determine the level of BDFT occurring in helicopters. In this study, BDFT was measured for the collective and the cyclic control devices, in roll, pitch, and vertical direction, for three different control tasks, a position task (PT) or 'stiff task', a force task (FT) or 'compliant task', and a relax task (RT). The study focuses on the influence of the pilot's neuromuscular dynamics on the level of BDFT. Two major conclusions can be drawn from the experimental results: 1) BDFT in helicopters is task dependent 2) the highest level of BDFT is measured in lateral direction, followed by longitudinal and finally vertical direction.
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Publication date	September 2012
Reference	ICAS Brisbane

ARISTOTEL

Title	**PIO (Pilot Induced Oscillations) Criteria for Rotorcraft Pilot Coupling (RPC) in roll axis investigation**
Objective(s)	Objective 4
Abstract	Advances in Flight Control System (FCS), cockpit controllers and aircraft effectors with a significant level of automation in generally have intention to relieve pilot workloads and to allow operations in degraded weather and visibility conditions. Fixed and rotary wing pilots are being confronted with potential instabilities or with annoying limit cycles oscillations, knowing that Aircraft- and-Rotorcraft-Pilot Couplings (A/RPC) that arise from the effort of controlling vehicle with high response actuators. Research experience concerning pilot-in-the-loop handling qualities show that understanding, predicting and suppressing of inadvertent or sustained rotorcraft oscillations has received less attention until the last two decades. This paper develops the existing bandwidth - phase delay PIO I Category criteria on aircraft to analyze rotorcraft oscillatory or divergent behavior from adverse pilot vehicle coupling. Bandwidth-phase delay criteria can be used to evaluate rotorcraft susceptibility to PIO Categories I. The proposed criteria are applied to the analysis of a medium weight helicopter model and a/the closed – loop parameter is assessed through numerical simulation.
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Publication date	October 2012
Reference	"AEROSPATIAL 2012" Conference Proccedings
DOI	ISSN 2067-8614

CONFERENCE PROECCINGS

Title	**Rotorcraft Pilot Impedance from Inverse Dynamics-Based Biomechanical Model**
Objective(s)	Objective 3
Abstract	The involuntary interaction of the pilot with a vehicle is often an undesired consequence of the biomechanical properties of the human body and its relation with the layout of the manmachine interface. This work discusses how muscular activation patterns affect the variability of the equivalent impedance of helicopter pilots. A multibody model is used to compute the joint torques associated to a prescribed pilot task, which are then transformed into corresponding 'optimal' muscular activation patterns. Equivalent pilot impedance is obtained by consistently linearizing the constitutive model of the muscles about the reference activation. The effect on equivalent impedance of nonoptimal activation, resulting from the addition of Torque-Less Activation Modes to the optimal activation, is evaluated and discussed.
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Publication date	November 2012
Reference	Proceedings of the ASME 2012 International Mechanical Engineering Congress & Exposition

Title	**Coupled Bioaeroservoelastic Rotorcraft-Pilot Simulation**
Objective(s)	Objective 2
Abstract	This work presents the integration of a detailed biomechanical model of the arms of a helicopter pilot and an equivalently detailed aeroservoelastic model of a helicopter, resulting in what has been called a 'bioaeroservoelastic' analysis. The purpose is to investigate potential adverse interactions, called rotorcraftpilot couplings, between the aeroservoelastic system and the controls involuntarily introduced by the pilot into the control system in response to rotorcraft vibrations transmitted to the pilot through the cockpit, the so-called biodynamic feedthrough. The force exerted by the pilot on the controls results from the activation of the muscles of the arms according to specific patterns. The reference muscular activation value as a function of the prescribed action on the controls is computed using an inverse kinetostatics/ inverse dynamics approach. A first-order quasi-steady correction is adopted to mimic the reflexive contribution to muscle activation. Muscular activation is further augmented by activation patterns that produce elementary actions on the control inceptors. These muscular activation patterns, inferred using perturbation analysis, are applied to control the aircraft through the pilot's limbs. The resulting biomechanical pilot model is applied to the aeroservoelastic analysis of a helicopter model expressly developed within the same multibody modeling environment to investigate adverse rotorcraft pilot couplings. The model consists of the detailed aeroelastic model of the main rotor, using nonlinear beams and blade element/momentum theory aerodynamics, a component mode synthesis model of the airframe structural dynamics, and servoactuator dynamics. Results in terms of stability analysis of the coupled system are presented in comparison with analogous results obtained using biodynamic feedthrough transfer functions identified from experimental data.
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Publication date	August 2013
Reference	Proceedings of the ASME 2013 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE

CONFERENCE PROECCINGS

Title	**Effect of Manipulator Feel System Characteristics on HQ of Aeroelastic Aircraft**
Objective(s)	
Abstract	In the paper some results are presented, which were received in the course of project ARISTOTEL conducted within the 7th European Framework Program (FP7 266073). It is known [1] that the role of angular and linear accelerations arising in flight is dual: in some cases it is beneficial (accelerations are informative factor); in other cases it is negative (accelerations are negative factor). The high-frequency accelerations due to turbulence or those resulting from pilot activity due to inadequate aircraft characteristics can be attributed to the negative, or “biodynamical”, factor. The high-frequency accelerations arising as a result of pilot activity can be subdivided into two groups: that ones which are caused by inadequate characteristics of rigid-body aircraft, and that ones which are caused by aircraft structural elasticity. For rigid-body aircraft, the authors of Ref.[2,3] proposed a theoretical approach to assess the effect of high-frequency accelerations arising during so-called aircraft abrupt response (AR) to pilot activity. The high-frequency accelerations due to structural elasticity cause negative effect as well since they lead to involuntary body and limb-manipulator system displacements, which interfere with pilot voluntary control activity (biodynamic interaction) and, finally, worsen handling quality ratings. Thus, it seems reasonable to apply the main idea of the theoretical approach stated in [2,3] to assess the effect of structural elasticity. Recent experimental data [4] show that the type of manipulator and its feel system characteristics can affect intensity of the biodynamic interaction in pilot-aircraft system. But, mathematical expressions in the theoretical approach do not take into account their effects. Thus, the goals of the present paper are: To develop and validate criteria to assess effect of structural elasticity on pilot rating worsening. Experimental study of the effect of manipulator feel system characteristics on handling qualities of aero-elastic aircraft, and modification of the criteria to take the effect into account.
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Publication date	August 2013
Reference	AIAA Conference Proceedings

Title	**Investigation of Adverse Aeroelastic Rotorcraft-Pilot Coupling Using Real-Time Simulation**
Objective(s)	Objective 1, Objective 5
Abstract	This paper presents the results of a flight simulator test campaign aimed at understanding the effect of high-frequency dynamics associated with helicopter aeroservoelasticity on the proneness to rotorcraftpilot couplings and specifically to pilot-assisted oscillations. Linearised aeroservoelastic models representative of helicopters in hover and in forward flight have been flown in a full motion flight simulator by trained test pilots, performing selected mission task elements. The handling qualities of the vehicles have been intentionally degraded by modifying the gearing ratios between the control inceptors and the flight controls and by introducing time delays representative of realistic fly-by-wire flight control systems. Clear evidence of pilot-induced oscillations has been found while performing the roll step manoeuvre, especially with the soft-inplane hingeless helicopter with a lightly damped main rotor first regressive lead-lag mode. Based on subjective pilot ratings and objective measures, the aeroservoelastic models require higher pilot workload than corresponding rigid-body models. The repeatable occurrence of an unstable pilot-assisted oscillation event with only one test pilot flying the aeroservoelastic model has been explained by the interaction of the pilot's involuntary biodynamic feedthrough, identified by specific experiments, and the above mentioned regressive lead-lag mode.
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Authors	V. Muscarello, P. Masarati, G. Quaranta, L. Lu, M. Jump, M. Jones
Involved institution(s)	POLIMI, UoL
Publication date	2013
Reference	69th AHS Forum Conference Proceedings

Title	**Rotorcraft Pilot Coupling Susceptibility Accompanying Handling Qualities Prospects in Preliminary Rotorcraft Design**
Objective(s)	
Abstract	Parallel to the evolution of sophisticated enhancements in rotorcraft technology and subsystems, flight test programs have been troubled with a persistent safety phenomenon: Pilot Induced Oscillations (PIO's), which are considered under the umbrella of a wider interaction group called Aircraft/Rotorcraft Pilot Couplings (A/RPC's). Starting from the first powered flight, both fixed and rotary wing platforms have been experiencing this safety threatening closed loop phenomenon, thus, various prediction and prevention tools have been developed. Recently, the European Commission 7th Framework Programme project ARISTOTEL project aimed to investigate the state of the art A/RPC status. One of the targets of the project is to provide guidelines to designers and simulator programs to reveal A/RPC aspects of the vehicle to be designed or to be evaluated. Due to expensive and risky A/RPC flight testing phases of an aircraft development program, it is highly beneficial to crosscheck the A/RPC susceptibility of the vehicle as early as possible during the design process. This study aims to unmask effects of preliminary rotorcraft design parameters on Handling Qualities (HQ's) and RPC's, through the application of the Bandwidth Phase Delay (BPD) criterion contained ADS-33, Open Loop Onset Point (OLOP) criterion, and the novel Predictive Phase-Aggression Criterion (PRE-PAC). respectively. Briefly, BPD criterion is an application of a pure-gain pilot crossover model which determines the maximum closed-loop crossover frequency that the system can have without risking the instability. Phase delay partition of the criteria reflects the tendency of the system to expose phase drop beyond neutral stability point of the system. OLOP is defined as the frequency response value of the open-loop system at the closed-loop onset frequency. This frequency is the point at which actuator saturation first occurs. The closed-loop system describing function is characterised by a jump phenomenon after rate limiting onset, which can be recognized in a Nichols chart as a significant phase jump. PRE-PAC is a tool which has been developed from a real-time capable algorithm, specifically for the predictive appraisal of PIO susceptibility. The algorithm uses defined sinusoids with varying magnitude and frequency to determine the regions of pilot control whereby vehicle response characteristics cross PAC susceptibility boundaries. Complete details of stated criteria will be described in the full paper. Finally, correlations between BPD, OLOP and PAC results for various design points will be elaborated in order to gain insight on trends of preliminary design parameter effectiveness on HQ and RPC prospects.
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Publication date	2013
Reference	39th European Rotorcraft Forum Proceedings

Title	**Biodynamic Pilot Modelling for Aeroelastic A/RPC**
Objective(s)	Objective 2, Objective 4, Objective 5
Abstract	This paper is about the European Commission 7th Framework Programme project ARISTOTEL (http://www.aristotel.progressima.eu/), which studies adverse interaction between pilots and aircraft. During the project, biodynamic pilot models have been identified to describe pilot-vehicle interaction under high-frequency accelerations. Such interactions occur as involuntary body and limb displacements, which introduce involuntary controls (biodynamic feedthrough, BDFT) that may degrade handling qualities and jeopardize stability. The frequency range and intensity of the oscillations depend on many factors: vehicle type, control system and structural dynamics, manipulator type and related feel system characteristics. Biodynamic pilot models are needed to investigate the worst combinations of the factors. Pilot models suitable for biodynamic interaction analysis can be divided in two main groups: • based on "Transfer function" approach, as a traditional and convenient analytical method to predict pilot-vehicle stability and handling qualities • based on "Multi-Body" approach, requiring identification of the properties of biomechanical models of aircraft pilots. • The two modeling approaches present interdependences; as long as a multibody model is validated using experimental data, it can be used as a numerical source of data for transfer functions in configurations similar to experimental ones without the need to resort to further experiments. Furthermore, multibody models can be used to thoroughly explore parameter variability with respect to pilot's size, muscular activation, and various other parameters.
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Authors	L. Zaichik, Y. Yashin, P. Desyatnik, P. Masarati, G. Quaranta, M. Pavel, J. Venrooij, H. Smaili
Involved institution(s)	TsAGI, POLIMI, TUD, NLR
Publication date	2013
Reference	39th European Rotorcraft Forum Proceedings

CONFERENCE PROCEEDINGS

Title	**An Approach to Assess Aircraft-Pilot Coupling Caused by Structural Elasticity**
Objective(s)	
Abstract	The authors proposed a theoretical approach to assess the effect of high-frequency accelerations arising during so-called aircraft abrupt response (AR) to pilot activity. The high-frequency accelerations due to structural elasticity cause negative effect as well, since they lead to involuntary body and limb-manipulator system displacements, which interfere with pilot deliberate control activity (biodynamic interaction) and, finally, worsen handling quality ratings. As the idea of the theoretical approach in [4] has a general meaning, it seems reasonable to apply it for the assessment of structural elasticity effect, and to extend for rotary-wing aircraft.
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Publication date	2013
Reference	39th European Rotorcraft Forum Proceedings

Title	**Anatomy, Modelling and Prediction of Aeroservoelastic Rotorcraft-Pilot-Coupling**
Objective(s)	Objective 3, Objective 6
Abstract	Research activity and results obtained within the European project ARISTOTEL (2010-2013) are presented. It deals with anatomy, modelling and prediction of Rotorcraft Pilot Coupling (RPC) phenomena, which are a really broad and wide category of events, ranging from discomfort to catastrophic crash. The main topics concerning piloted helicopter simulation that are of interest for designers are examined. These include comprehensive rotorcraft modelling suited for Pilot Assisted Oscillations (PAO) prediction, modelling of pilot biodynamics behaviour in the PAO frequency range of interest, definition and application of criteria for detection of RPC instabilities of aeroservoelastic nature. The numerical investigation considers Bo105 and IAR330 Puma helicopter models, as representatives of two different rotorcraft categories (small-size and medium-size helicopters, respectively). Factors affecting aeroservoelastic RPC prediction are investigated (like, for instance, pilot modelling, system modelling, number of controls on which the pilot exerts forces, control chain gearing ratios), with the aim of defining design guidelines for prevention of adverse RPCs occurrence.
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Involved institution(s)	UROMA3, POLIMI, UoL
Publication date	2013
Reference	39th European Rotorcraft Forum Proceedings

Title	**Exposing Rotorcraft Pilot Couplings Using Flight Simulation**	
Objective(s)		
Abstract	n/a	
Contact person	M. Jones	e-mail: Michael.Jones@liverpool.ac.uk
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Publication date	2013	
Reference	39th European Rotorcraft Forum Proceedings	

ARISTOTEL

Title	**Adverse Rotorcraft-Pilot Couplings: Modelling and Prediction Rigid Body RPC**
Objective(s)	
Abstract	Today's high performance aircraft and rotorcraft are a product of the ever increasing demands of operator requirements. They are faster and more capable, but are consequently more complex than their predecessors. During their development and subsequent operation, it appears that both, engineers and pilots must be prepared to deal with unfavourable phenomena, so-called "Aircraft/Rotorcraft Pilot Couplings" (A/RPCs). In the past frequently called "pilot induced oscillations/pilot assisted oscillations" (PIO/PAO), A/RPC are defined as "*inadvertent, sustained aircraft oscillations as a consequence of an abnormal joint enterprise between the aircraft and the pilot*" [ref. 1]. These undesirable oscillations may result in potential instabilities and limit cycle oscillations, degrading aircraft handling qualities and exceeding the vehicle structural strength limits. In 2010 the European Commission launched, under the umbrella of the 7th Framework Programme (FP7), the ARISTOTEL project (Aircraft and Rotorcraft Pilot Couplings – Tools and Techniques for Alleviation and Detection), the aim of which is to advance the state-of-the-art of A/RPC prediction and suppression. With a duration of 3 years (2010-2013), and involving partners from across Europe, the ARISTOTEL project's objectives were to improve the understanding of present and future A/RPCs. Based on the experience of previous projects related to A/RPCs in both Europe and United States of America [refs. 1-17], the ARISTOTEL project has divided the A/RPC range of incidents into two categories (see Figure 1): 1) lower frequency range A/RPC or "rigid-body A/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 A/RPC or "aeroelastic A/RPC" corresponding to higher frequency dynamics, i.e. elastic airframe and main rotor blades modes, which involve more a passive pilot subjected to vibrations. Extended rigid body RPC underlines the importance of higher order rotor dynamics on the flight mechanics modelling for rotorcraft capturing vehicle-pilot coupling phenomena up to 3Hz. The goal of the present paper is to give an overview of the progress in the work performed by the ARISTOTEL project on understanding, modelling and predicting rigid body RPC.
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Publication date	September 2013
Reference	39th European Rotorcraft Forum Proceedings

CONFERENCE PROCEEDINGS

Title	**Biodynamic Pilot Modelling for Aero- Elastic Aircraft**
Objective(s)	
Abstract	In the paper, the models of biodynamic pilot are identified to describe biodynamic pilot- aircraft interaction under high- frequency lateral accelerations. The results presented are received in the course of project ARISTOTEL performed within the 7th European Framework Program, and are further development of that shown in [1]. In perspective, the results will be used to develop criteria to assess the effect of structural elasticity on aircraft handling qualities. As it is shown in Figure 1, depending on the piloting task, one or more acceleration feedbacks can arise in addition to the visual feedback. As it was shown in [2], the effect of the accelerations, beneficial or negative, depends on the piloting task, acceleration intensity and aircraft characteristics. The accelerations due to structural elasticity are of high frequency and play negative role in piloting. Such accelerations can cause involuntary body and limb-manipulator displacements (biodynamic interaction), which, in turn, can intensify the high- frequency oscillations and lead to handling quality pilot rating degradation.
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Publication date	2013
Reference	EUCAS 2013 Proceedings

Title	**Assessment of a State-Space Aeroelastic Rotor Model for Rotorcraft Dynamics Analysis**
Objective(s)	Objective 3, Objective 4, Objective 6
Abstract	The aim of the paper is the assessment of a methodology for the identification of helicopter rotor state-space aeroelastic representation relating hub motion and blade pitch controls to the loads transmitted to the fuselage. It is suited for the simulation of the dynamics of comprehensive complete helicopter configurations, particularly in application concerning analysis of rotorcraft-pilot coupling (RPC) phenomena, as well as synthesis control laws. Observing the inherently time-periodic nature of theoretical formulations describing rotor aeroelasticity, the state-space form identification method consists of a three-step process in which filtering of spectra of responses to small-perturbation harmonic inputs is followed by the rational form approximation of the corresponding transfer functions. Considering a Bo-105-type helicopter, the numerical investigation is focused on: analysis of critical parameters for an accurate and efficient identification of transfer functions, interpretation of the additional states related to their rational approximation, validation of the state-space rotor aeroelastic representation, and application to RPC aeroelastic phenomenon. Further, the sensitivity of rotor aeroelastic operator and correspondingly RPC simulations to different aerodynamic load models is also investigated.
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Publication date	September 2013
Reference	XXII AIDAA Conference

CONFERENCE PROCEEDINGS