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NUMERICAL INVESTIGATION OF AEROSERVOELASTIC ROTORCRAFT-PILOT COUPLING

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ABSTRACT

This paper describes the current status and achievements of a research activity for the investigation of rotorcraft-pilot coupling (RPC) governed by aeroelastic issues, to single out possible sources and occurrences of the phenomenon, focused on the determination of possible design solutions towards RPC-free helicopters and rotorcraft in general. A brief presentation of the numerical analysis methodologies used by the two research teams introduces the description of the benchmark used in this analysis, which is completed by a summary of the results obtained in recent investigations.

1. BACKGROUND AND SCOPE

The interaction between the aircraft and the pilot represents a potential threat to the airworthiness of any kind of flying vehicles. The history of aircraft has seen the appearance of unfavorable Aircraft-Pilot Coupling (APC) from the very beginning, when aircraft controllability was the issue to overcome to achieve human flight. Subsequent progress in aircraft design led to higher performance and broader flight envelope; at the same time, the amount of workload for the pilot and the crew has been reduced by providing substantial automation in aircraft control. However, the need for the crew to deal with other tasks reduced the time share of their attention that is dedicated to flying the aircraft. This, in critical flight conditions, gives room for unfavorable APCs when some unexpected event triggers an abnormal aircraft behavior.
Unfavorable APCs are defined as

> "... inadvertent, sustained aircraft oscillations which are a consequence of an abnormal joint enterprise between the aircraft and the pilot..." [1]

This means that the presence of the pilot plays a fundamental role in the phenomenon, but other players participate: the vehicle, the mission task, and a trigger, namely an abnormal event that alters the coupled vehicle-pilot system's conditions, initiating the adverse phenomenon.
APCs are undesirable and sometimes hazardous phenomena associated with less-than-ideal interactions between the pilot and the aircraft. Although not always catastrophic, they can range in severity from minimally affecting operational missions, by degradating the capability to perform a certain mission task within the requirements, to loss of aircraft or lives.
The available literature mainly focuses on the investigation of problems that directly involve an active participation of the pilot: the so-called Pilot-Induced Oscillations (PIO) [2–4]. There are clear examples in the history of aircraft and, although less reported and only recently documented, of rotorcraft [5,6], resulting in the so-called Rotorcraft-Pilot Coupling (RPC) phenomena. The resulting oscillations may endanger the safe execution of a mission task and, unless stopped, cause severe damage to the vehicle, or even its loss.
Furthermore, both fixed and rotary wing aircraft are potentially prone to adverse interactions that involve the pilot in a purely passive, or semi-active, manner: the so-called Pilot-Augmented Oscillations (PAO), where the pilot acts

as sort of a mechanical impedance between dynamically and aeroelastically induced vibrations of the body, and the resulting inputs that are inadvertently fed into the control system. Also this type of problems is more commonly investigated for fixed wing aircraft [7].
Occasionally, problems related to the semi-active behavior of the pilot may occur as a consequence of a pilot's reflexive attempt to counteract the aircraft behavior beyond the pilot's bandwidth, thus somehow overlapping with the upper boundary of the frequency spectrum of the active pilot's case, which is usually does not exceed 1 Hz.
While fixed-wing aircraft dynamics, with few notable exceptions typically related to large size aircraft, are typically well-separated from rigid body motion, resulting in aeroelastic vibrations well beyond the bandwidth of the pilot, helicopters and rotorcraft may show significant interactional dynamics at very low frequencies, resulting from the coupling of:

- the rigid body rotorcraft dynamics;
- the rotor dynamics, including rotor aeroelasticity;
- the dynamics of the pilot;
- the dynamics of the airframe,

which, under specific circumstances, may result in unstable behavior.
In this paper, no specific investigation of the physiology of the pilot is pursued; however, it is assumed that, in analogy to active PIO, the compliance of the pilot in assisting the PAO may change as a consequence of variations in the workload, in the level of attention, in the specific mission task element (MTE) or in the available cues. It is the change in the pilot's impedance that triggers the instability; subsequently, the onset of the adverse oscillations by itself alters the level of attention of the pilot and changes the cues the pilot mainly focuses on, potentially worsening the behavior.
This activity has been performed by the Universities "Roma Tre" and "Politecnico di Milano" in the framework of the GARTEUR HC AG-16 cooperative effort for the investigation of specific issues related to active and passive pilot interaction with rotorcraft. Special focus has been dedicated to the passive interaction of the pilot with the rotorcraft aeroelasticity. The activity is still ongoing and will end within 2007, including, among other, experimental investigations of the biomechanical and aeroelastic aspects of the interaction, supported by dedicated flight simulator campaigns performed at the University of Liverpool.
This paper describes part of the activity performed in preparation of the experimental campaigns. A more specific investigation of the physiological aspects of the modifications in the pilot's impedance related to the workload could be part of future efforts, where the very positive experience gathered during the GARTEUR cooperation with other European Universities, aerospace research centers and rotorcraft industries will likely be exploited.

2. PROBLEM DESCRIPTION AND OBJECTIVES

The popular Bo105 helicopter (Figure 1), although not specifically known to be prone to this type of problems, has been selected as a test bed for the numerical investigation that represents the subject of this work. The main reason is the public availability of a wealth of general information and technical data on this specific rotorcraft, but another reason it the possibility, owing to its peculiar high controllability characteristics, to introduce potentially adverse couplings with the pilot by means of limited changes in the control chain, including the physiological properties of the pilot itself. In this sense, this work does not address specific problems encountered by a real rotorcraft, but rather the potential for problems of this type within generic rotorcraft, introduced by adequately tweaking interactional parameters.

2.1. The "Vertical Bouncing" Problem

Particular attention has been devoted to the so-called "vertical bouncing" problem (Fig. 2), where the cone mode of the main rotor, excited by the vertical motion of the vehicle, couples with the collective control inadvertently introduced by the pilot as a consequence of vertical oscillations of the entire airframe and of vertical oscillations related to the deformation of the fuselage. This mode shows a large potential for unfavorable coupling:

- the vertical motion of the airframe can have significant coupling with collective flapwise bending (cone) of the main rotor blades;
- the vertical motion of the airframe can also couple with the vertical bending of the fuselage;

Figure 1: Bo105 operated by DLR FT at Braunschweig.

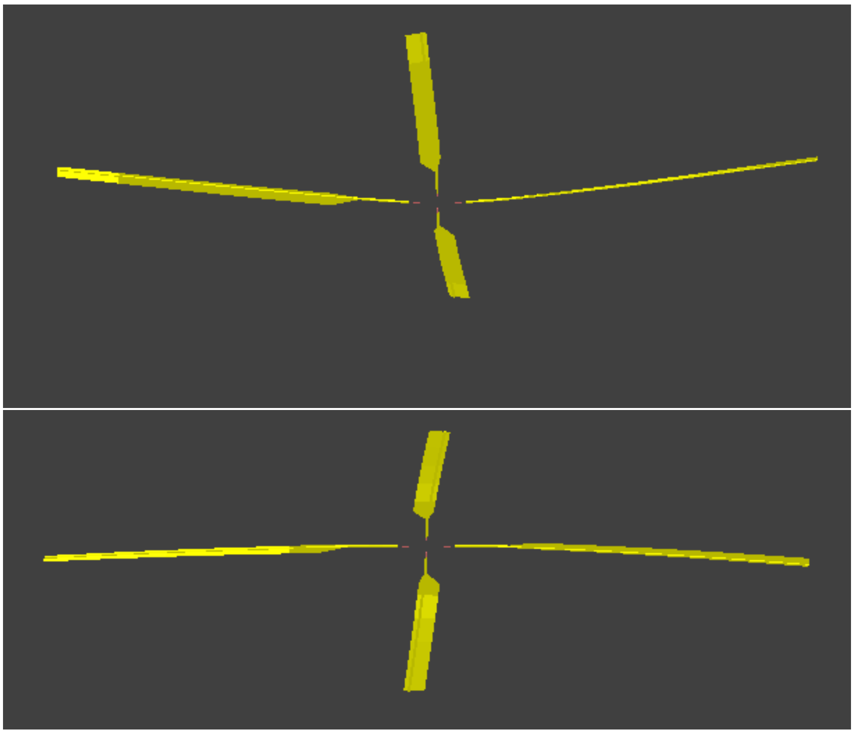

Figure 2: Unstable vertical bouncing mode shape (in the rotating frame).

- the vertical motion of the fuselage, both related to the rigid-body motion and to the fuselage bending causes vertical accelerations of the pilot;
- the resulting vertical motion of the pilot may cause collective bar excitation through the pilot's arm;
- the motion of the collective bar changes the imposed pitch of the main rotor blades, resulting in changes in the rotor thrust;
- the dynamic change in main rotor blade pitch, even though presumably at low frequencies, may statically excite blade twist, resulting in further amplification of blade aerodynamic loads;
- the collective excitation may excite the collective lead-lag mode, which is tightly coupled to drive train modes (this aspect has been ignored so far, due to a lack of data about drive train dynamics).

It is clear that the numerical analysis of this problem requires the capability to simultaneously model several aero(servo)elastic aspects of rotorcraft dynamics to a degree of refinement that allows to capture at least the order of magnitude of the relevant couplings. The problem has been addressed by the two research teams using different approaches, as described in the following.

2.2. Analysis Approach

The highlighting of this problem is separated in two steps:

1. the development and validation of a reliable aeroservoelastic model of the rotorcraft that allows to consider all the coupling terms that might be relevant in the phenomenon;
2. the selection of parameters that might be reasonably perturbed in order to assess the stability properties of the system and its sensitivity with respect to this specific dynamic event.

The model is described in detail in the following; with respect to sensitivity parameters, focus is set on the "gain" of the passive pilot, where the term gain is somehow arbitrarily related to a scale factor to be applied to the pilot model to emphasize the feedback he might inadvertently send to the collective control in reaction to vertical oscillations of the cockpit.

3. MODEL DESCRIPTION

The model of the helicopter consists in several subcomponents that closely resemble those of the real vehicle or, occasionally, idealizations of real subcomponents that are required by the analysis procedure.

3.1. Main Rotor

The most detailed component, from a structural dynamics point of view, is the main rotor; in fact, the aeroelasticity of the main rotor is believed to dominate the phenomenon. It is a 4-bladed, soft-inplane hingeless rotor, characterized by a nominal radius of 4.9 m and a nominal angular velocity of 44.4 rad/s (slightly above 7 Hz). The lead-lag frequency at 100% rpm is slightly above 5 Hz, but the rotor has no lead-lag damper; damping of the inplane blade motion is delegated to a peculiar friction-based mechanism in the hingeless blade root.

A complete aeroelastic database of the Bo105 main rotor has been gathered, and aeroelastic models have been validated by comparing the rotor frequencies in-vacuo and the rotor loads as functions of the collective in hover. Data has been provided by Mr. O. Dieterich [8], and Mr. J. Götz, [9], whose essential contribution is sincerely acknowledged.

3.2. Tail Rotor

The tail rotor, on the contrary, is believed to have a limited impact on this specific problem, because it is very rigid and characterized by frequencies, related to the angular velocity, that are much higher than those of the main rotor (233 rad/s, about 37 Hz, with a tail to main rotor velocity ratio of 5.25). In most cases, the tail rotor may be safely replaced by a force granting the required anti-torque effect, since no aerodynamic interaction between the two rotors has been considered so far.

3.3. Airframe

The airframe connects all subcomponents, and thus is in charge of establishing kinematic relationships between the forces generated by the rotors and the accelerations of the pilot. Furthermore, when its own deformability is accounted for, it contributes to the dynamics of the system.

The dynamics of the fuselage has been considered in terms of normal modes, namely frequencies, modal masses and mode shapes at selected points that have been considered relevant for this specific analysis. Data has been provided by Mr. O. Dieterich [10].

The points whose motion is described by the mode shapes are related to main and tail rotor connections and to pilot and co-pilot location in terms of floor and seat attachments. Although helicopters do not have an exact plane of symmetry, the lowest frequency mode shapes considered in this work showed a nearly symmetric/skew-symmetric behavior. Nonetheless, it is anticipated here that the slight differences in the modal displacement of the pilot/co-pilot seat attachments resulted in appreciably different contributions to the stability of the system.

In order to give an idea of the relative effects of the subcomponents, the frequency of the lowest mode, consisting in the bending of the airframe about the pitch axis and computed with the main rotor simulated by a point mass, is 5.8 Hz. However, when the airframe is coupled to the rotor dynamics, and significantly with the cone bending of the rotor blades, the frequency drops by 5% to about 5.5 Hz.

From an aerodynamic point of view, the airframe was experimentally characterized in terms of steady rigid-body aerodynamic forces and moments depending on the pitch and yaw angles, including those of the horizontal and vertical tail surfaces, which contribute to the trim of the rotorcraft but do not otherwise interact with the rotor aerodynamics.

3.4. Control System

The control system connects the displacement of the controls to changes in the pitch of the main rotor blades. In this problem, only the collective control is considered, as it is assumed to be the one most influenced by vertical oscillatory motion of the pilot. The input of the pilot results in some input into the hydraulic control system of the swashplate of the main rotor. The transfer function between the input requested by the pilot and the actual motion of the swashplate is modeled as

$$\theta = \frac{1}{1+\tau s}\left(\theta_{0\%} + \left(\theta_{100\%} - \theta_{0\%}\right)\frac{\delta_c}{100}\right) \tag{1}$$

where δ_c is the collective input in % of stroke, and τ is the time constant of the first-order approximation of the closed-loop hydraulic actuator.

3.5. Pilot Mechanical Impedance

The mechanical impedance of the pilot represents perhaps the subcomponent with most uncertainties, because it depends on so many parameters. First of all, it necessarily is the result of some averaging between pilots with different physiological characteristics. According to the analysis presented in [11], two transfer functions between the acceleration of the seat and the acceleration of the collective bar at the handle are identified for what the Author termed the "ectomorphic" (= smaller size) and the "mesomorphic" (= larger size) pilots.

Those functions are the result of fitting measurements performed by vertically shaking 3 persons of each category in a cockpit mock-up that is supposed to be representative of a generic heavy helicopter.

The mesomorphic pilot transfer function is

$$H_{\text{meso}}(s) = \frac{4.02s + 555.4}{s^2 + 13.31s + 555.4}, \tag{2}$$

while that of the ectomorphic one is

$$H_{\text{ecto}}(s) = \frac{5.19s + 452.3}{s^2 + 13.7s + 452.3}. \tag{3}$$

Note that the poles of the mesomorphic pilot are $-6.655 \pm 22.608i$, while those of the ectomorphic one are $-6.850 \pm 20.134i$, corresponding to 3.6 Hz vs. 3.2 Hz and 28% vs. 32% of critical damping.

The transfer functions of Equations (2) and (3) refer to an average setting of the collective bar towards 0%; it has been observed in [11] that higher collective settings, more representative of a hover and forward-flight trim condition, in the vicinity of the resonance, at 3 Hz, yield a lower gain between the seat and the control acceleration, up to a factor of 0.5, thus alleviating the coupling.

The approach followed in [11], which is typically found in the literature on the subject [6, 12], although considered acceptable at this stage, suffers from the limitation that the equivalent transfer function of the pilot results from fitting experimental data about a specific reference condition of the pilot. To overcome this limitation, an experimental campaign is being performed within GARTEUR HC AG-16 to gain some broader insight into the biomechanical behavior of the pilot, and possibly allow the direct use of more sophisticated biomechanical models. It is worth stressing that so far a purely mechanical effect of the aircraft motion on the feedback the pilot inadvertently sends to the controls has been considered. In modern helicopters, an Automatic Flight Control System (AFCS) would be part of the loop, and the input sent by the pilot to the control system by means of haptic interfaces would be filtered and modified by the AFCS before being turned into the actual swashplate input command. As a consequence, the aeroservoelastic analysis of a real modern helicopter would definitely require the incorporation of the AFCS dynamics.

4. RPC MODELING AT UNIVERSITY ROMA TRE

The numerical algorithm through which the pilot-in-the-loop aeroelastic analysis of a helicopter is performed is based on the coupled equations describing airframe aeromechanics, rotor aeroelasticity and pilot dynamical behavior. In the following, the modeling of these in-flight rotorcraft components is briefly outlined and the links among them are defined.

The dynamics of the helicopter fuselage is described through the well-known Euler equations for a six-degree of freedom rigid-body motion, with forcing terms given by main and tail rotor loads transmitted at the hubs and by the airloads generated on fuselage, fin and tail plane surfaces. In order to take into account the effects of the airframe elastic deformation, the rigid-body model described by the nine rigid-body motion state variables (translational and rotational velocities, plus the three Euler angles) is enriched by inclusion of the elastic degrees of freedom associated to the normal vibration modes of the fuselage.

These elastic Lagrangean coordinates are governed by a set of second-order linear differential equations with mass and stiffness matrices obtained by means of a FEM analysis validated by ground vibration tests [10] which, from the structural point of view, is uncoupled from the rigid-body motion equations, since the modal analysis has been evaluated under free-body constraint conditions (i.e. natural modes of vibration and rigid-body ones are mutually orthogonal). However, fuselage deformations affect main/tail rotor-fuselage interactions. Indeed, the elastic deformations combined with the rigid-body motion yield the linear and angular hub displacements that produce perturbations to the inertial and aerodynamic loads on the rotor blades, in turn, forcing fuselage equations of motion through transmission at the hubs.

The modeling of the structural dynamics of the main rotor blades is based on the nonlinear flap-lag-torsion equations of motion presented by Hodges and Dowell [13]. These are related to a beam-like model and are valid for straight, slender, homogeneous, isotropic, nonuniform, twisted blades undergoing moderate displacement. In this model, second order terms are retained in the equations after application of an ordering scheme dropping third-order terms (with respect to bending slope) not contributing to damping. The radial displacement is eliminated from the set of equations by solving it in terms of local tension, and thus the resulting structural operator consists of a set of coupled nonlinear integro-partial differential equations governing the bending of the elastic axis and the blade torsion [13]. These equations have aerodynamic forcing terms consisting of lagwise and flapwise sectional forces and sectional pitching moment which, here, are obtained from a two-dimensional, quasi-steady aerodynamic model with wake-inflow correction given either by an analytical model or by a free-wake analysis based on the boundary integral aerodynamic solver described in Ref. [14]. The spatial integration of the main rotor aeroelastic system is obtained by the Galerkin method, using the natural vibration modes of the nonrotating blade as mode shape functions [15]. It yields a set of second-order ordinary differential equations for the blade Lagrangean variables, coupled with the fuselage motion through the inertial and aerodynamic terms depending on it.

The pilot model included in the rotorcraft aeroelastic loop is that presented by Mayo [11]. It is a passive model that takes into account the effect of involuntary pilot control inputs due to helicopter vertical motion. Both for mesomorphic and ectomorphic subjects the biodynamic pilot models are given in terms of a transfer functions between pilot seat vertical acceleration and collective stick vertical acceleration [11]. Through a second order dynamic model of the control chain the stick vertical displacement is related to a change in the blade collective pitch angle that, in turn, provides aerodynamic load perturbations affecting the main rotor aeroelastic response and, consequently, the rotorcraft dynamic behavior. The inclusion of a biodynamical pilot model in the helicopter aeroelastic loop allows the anaysis of the reduced stability of vertical bouncing that may occur due to the amplifications to perturbations given by the pilot reaction to helicopter unsteady motion.

The set of coupled equations governing the motion of the elastic airframe, the dynamics of main rotor blades and the biodynamical pilot behavior is linearized about a steady periodic equilibrium state through a numerical

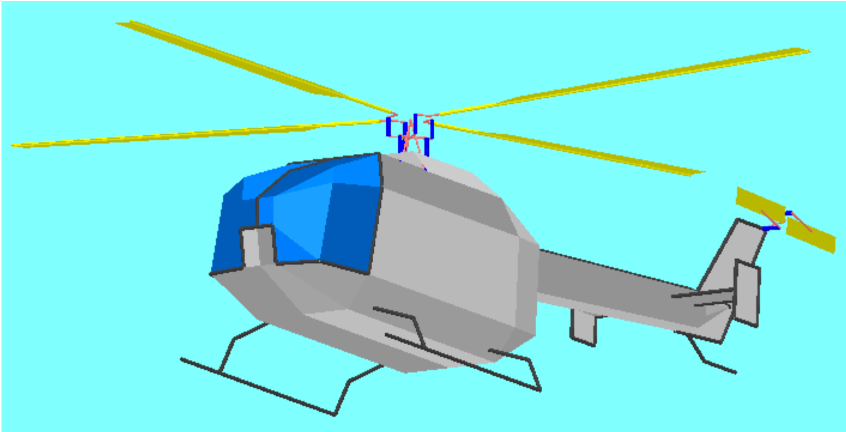

Figure 3: MBDyn model of the Bo105.

procedure. Then, the Floquet theory is applied to the resulting set of periodic-coefficient ordinary differential equations in order to perform the eigenvalue stability analysis of the closed loop fuselage/rotor/pilot dynamics.

5. RPC MODELING AT POLITECNICO DI MILANO

The model developed at Politecnico di Milano is based on a general-purpose multibody modeling approach. Each of the subcomponents described earlier is modeled using the free multibody analysis software MBDyn [16–18]. This software is mainly intended for the solution of Initial Value Problems by direct time integration, typically by using unconditionally stable implicit integration algorithms [19]. It allows to model multidisciplinary problems by providing a built-in multiphysics element library that can be easily expanded by the user.

With respect to the modeling of mechanical and aeroelastic systems, the problem is described in terms of the kinematics of nodes, which represent entities that provide public degrees of freedom, connected by elements, which represent entities that write down the kinematic and dynamic relationships between the public degrees of freedom, possibly along with private degrees of freedom as required (for example, the Lagrangean multipliers).

The dynamics of the structural nodes is written in terms of Newton-Euler equations in first-order form: for each node with inertia properties, six equations define the momentum and momenta moments, while six equations express the force and moment equilibrium of the node in terms of time derivatives of its momentum and momenta moment. Ideal kinematic nodes without inertia properties are specially dealt with by only writing the equilibrium equations; in this case, the node must be statically determined.

The kinematics of the nodes can be arbitrarily constrained by algebraic constraints; in this case, the constraint equations are explicitly added to the system, resulting in Lagrangean multipliers applied to the equilibrium equations of the nodes as appropriate, according to the redundant coordinate formulation paradigm. The resulting Differential-Algebraic system of Equations (DAE) is directly integrated by means of (nearly) L-stable integration algorithms.

The generality of the modeling approach allows to address problems characterized by arbitrary topology that are typical of a wide variety of engineering fields, not limited to rotorcraft or aerospace.

The multibody model of the Bo105 helicopter is sketched in Figure 3. The main rotor is modeled by geometrically nonlinear beam elements based on an original Finite Volume model [20], which allows to capture the dynamics of arbitrarily anisotropic rotating beams to the desired level of accuracy. The aerodynamics of the main rotor is based on the blade element theory, with simple inflow models. The kinematics and dynamics of the blade root, consisting in a flexbeam and a pitch bearing for each blade, is modeled without simplifications. The pitch control is also modeled in detail, by a set of bodies constrained by kinematic joints that control the position and attitude of the non-rotating portion of the swashplate, and the pitch links connecting each blade to the rotating portion of the swashplate.

The tail rotor is also modeled in detail, although not strictly required. The blades are rigid, each described by a node, so that their pitch is controlled by a pitch link. A paculiarity of the tail rotor is the teetering arrangement of the cyclic flapping, which shows a pronounced pitch-flap coupling of about 45 deg (pitch down when flap up). One drawback of modeling the tail rotor is that minimal accuracy requirements dictate the average angle spanned

by a time step, which is typically not larger than 10 deg. This may unnecessarily adversely affect the overall computational time, as the ratio between the tail and the man rotor angular velocity is 5.25.
The airframe is modeled by means of Component Mode Synthesis (CMS), by using a special element that superimposes the linear combination of deformation shapes to the arbitrary rigid-body dynamics of a node. The dynamics of the deformation shapes are governed by second-order linear differential equations, exploting the modal analysis results provided in [10]. The airframe model includes static aerodynamic forces depending on the pitch and yaw angles, as indicated in [9].
A peculiarity of this type of analysis is that it closely resembles an experiment, as trim and stability analysis cannot be decoupled since trim is reached in terms of a nearly-steady condition at the end of the integration of a transient. For this purpose, an external integral autopilot has been implemented in Simulink to control the flight of the helicopter up to the desired trim condition. Depending on the type of analysis, if a stable trim point is reached the autopilot can be either left in place or switchd off, to assess the stability of the uncontrolled system. This autopilot does not need to be realistic, since its purpose is limited to bringing (and eventually keeping) the system in a desired reference condition. As a consequence, no special care has been put into modeling real autopilot dynamics and behavior.
The passive pilot dynamics is modeled by adding either of the linear transfer functions of Equations (2) and (3) to the multibody model, connecting the input to the dynamics of the pilot/co-pilot seat as resulting from the combination of the rigid body and the CMS model accelerations, and adding the output to the desired collective pitch motion, in combination to any prescribed collective (e.g. the one used to perturb the trim) and any collective dictated by the autopilot. The resulting collective control input is filtered by the swashplate actuator transfer function of Equation (1) prior to controlling the actual displacement of the swashplate node.
The stability of the system is assessed by perturbing the trim condition, and by identifying the system response. Conventional system identification techniques can be used; in order to exploit the availability of significant redundancy from the simulation output, a technique based on the Proper Orthogonal Decomposition (POD) has been developed [21]. This approach allows to extract those signals that show significant participation in terms of signal energy, and significant spatial correlation, to build a reduced basis of signals that are used for the identification.

6. NUMERICAL RESULTS

This section presents a numerical investigation aimed at identifying the influence of aircraft and pilot modeling on the stability of the rotorcraft system. A complete Bo105 helicopter model has been simulated. The helicopter is trimmed for a mass of 2200 kg, close to the maximum gross weight of 2300 kg, for both hover and forward flight at nominal rotor speed, 44.4 rad/s.
University Roma Tre focused on the ectomorphic pilot [11], which was reported in the mentioned reference as the most prone to instability. A rigid body helicopter (i.e. without blade and fuselage elasticity) in hovering flight has been considered first. The stability analysis has been performed both without the pilot in the loop (gain = 0) and with the pilot in the loop (gain = 1). As shown in Figure 4 the inclusion of the pilot in the loop does not significantly affect the critical phugoid mode, while making the spiral mode (S) and the pilot mode (P) approach the stability boundary.
Politecnico di Milano experimented in hover with different combinations of pilot models and locations. The location of the pilot seems to have a minor impact on the stability properties, the co-pilot appearing as the least stable placement. This result is partially unexpected, because the differences in the mode shapes of the two locations are quite limited. Anyway, this result has been confirmed by independent (yet unpublished) analysis. The mesomorphic pilot appeared to be less stable than the ectomorphic one, as opposed to results from [11]. Also this result has been confirmed by independent analysis, and a possible explanation is that the mode that couples with the pilot and becomes unstable is related to fuselage bending with strong participation of main rotor cone. In the Bo105 this mode is at about 5.5 Hz, which is closer to the frequency of the mesomorphic pilot, 3.6 Hz, while in [11] a generic heavy helicopter was considered, with a presumably lower first fuselage bending frequency, thus possibly closer to the frequency of the ectomorphic pilot, 3.2 Hz.
Then the hovering helicopter analysis has been enriched by including of the both fuselage and rotor blade elastic degrees of freedom. Figure 5 depicts the stability eigenvalues computed without pilot in the loop for two fuselage elastic modes and different numbers of main rotor blade modes. This figure shows that the inclusion of elastic dofs induces the presence of many slighty damped modes, both describing blade dynamics and coupled rotor-fuselage dynamics. Note that one flap, lag and torsion blade mode seems to be sufficient to describe the aeroelastic behaviour of the helicopter. It has been observed that the presence of the blade twist mode appreciably reduces the stability margin of the fully coupled system, even though the first torsional frequency is much higher than that of

the vertical bouncing. Apparently, the nearly static response of that mode emphasizes the coupling with the cone mode by way of the aerodynamic forces.
Still considering the hovering elastic helicopter configuration, Figure 6 presents the effect of pilot inclusion in the loop. In detail it depicts the root loci for four different values of pilot transfer function gain. By comparison with Figure 4 one can observe that the presence of elastic dofs in the model increases the destabilizing effect of the pilot. The pilot mode gets much closer to the stability boundary describing vertical bouncing of the helicopter.
The results of the same kind of analisys are presented in Figure 7 for the helicopter in forward flight condition (65 KTAS), where a stronger destabilization effect of the pilot occours. In addition, the presence of the pilot causes the stabilization of the unstable mode which appears at this speed. the overall effect of the pilot in the loop seems to be more important in forward flight than in hover, probably because of the vibrations arising in forward flight tending to excite the pilot dynamics.
Finally we examine the effect of the inflow model used in the rotor aerodynamics model. In detail, the results from the analytical Drees model wake inflow are compared with those obtained through the wake inflow computed by a 3D unsteady BEM solver which is expected to have a higher armonic content. This comparison (see fig. 8) shows that the effect of a more realistic wake inflow is not negligible and in particular moves towards the stable region the poles that were initially unstable.
It is observed that, as expected, the addition of a notch filter on the output of the pilot transfer function, tuned on the pilot's frequency ($\sim$3.6 Hz), namely

$$H_{\text{notch}}(s) = \frac{s^2 + 0.315s + 516.5}{s^2 + 3.150s + 516.5} \tag{4}$$

completely cures the problem even in the worst case of mesomorphic co-pilot, as illustrated in Figure 9.

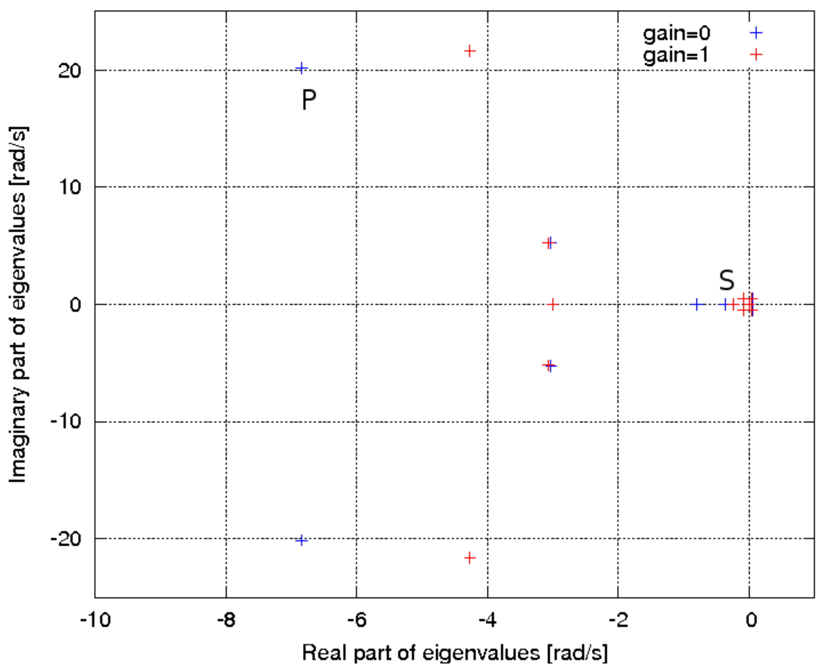

Figure 4: Root loci for rigid body model in hover.

7. CONCLUSIONS AND FUTURE ACTIVITIES

The investigation presented in this paper showed that fitting passive pilot dynamics models available from the literature into comprehensive multibody rotorcraft models may lead, under some circumstances typically related to excessive pilot gain, to unstable occurrences of the vertical bouncing. Parametric studies of this phenomenon have been undertaken to highlight which parameters mainly influence the phenomenon. Among them, it is worth mentioning that:

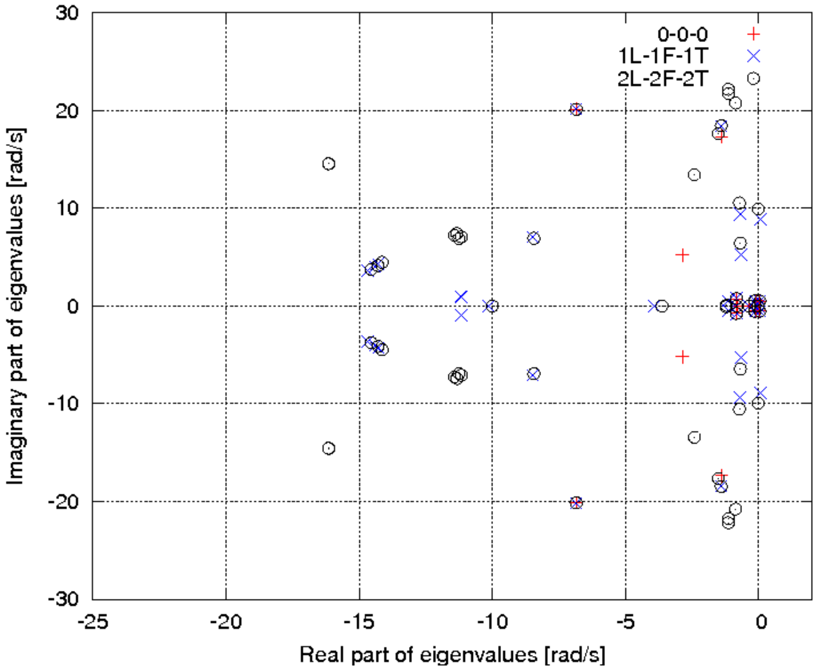

Figure 5: Influence of blade modes number on root loci in hover.

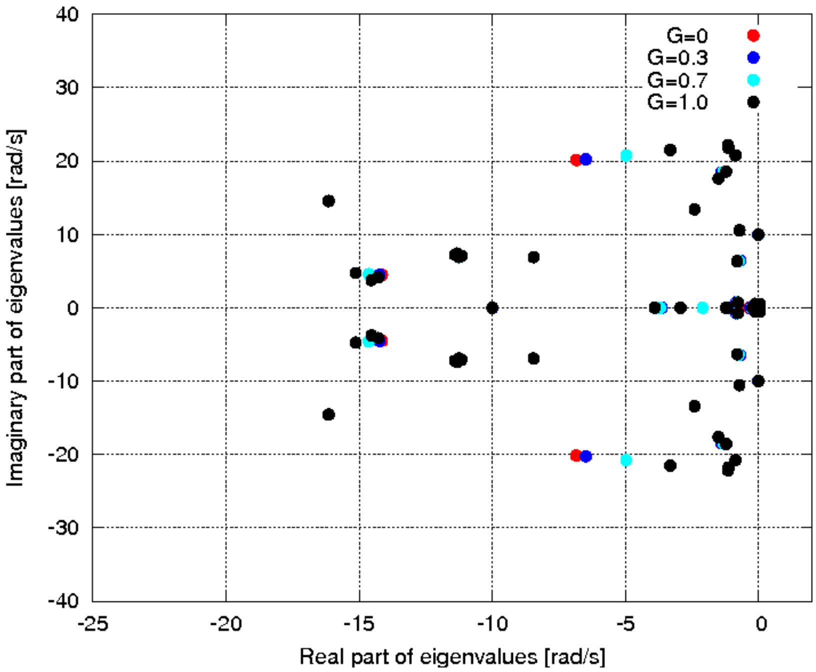

Figure 6: Root loci for complete helicopter model in hover.

- the phenomenon appears dominated by rotor cone motion, strongly coupled to vertical oscillations of the airframe and some relevant collective lag motion;
- there is a strong adverse influence of the blade torsional stiffness, since the phenomenon almost disappears if the torsional mode is neglected;
- there is a strong adverse influence of the fuselage deformability, since the phenomenon almost disappears if the first fuselage bending mode is suppressed, or if the participation of the pilot's seat to that mode is reduced;

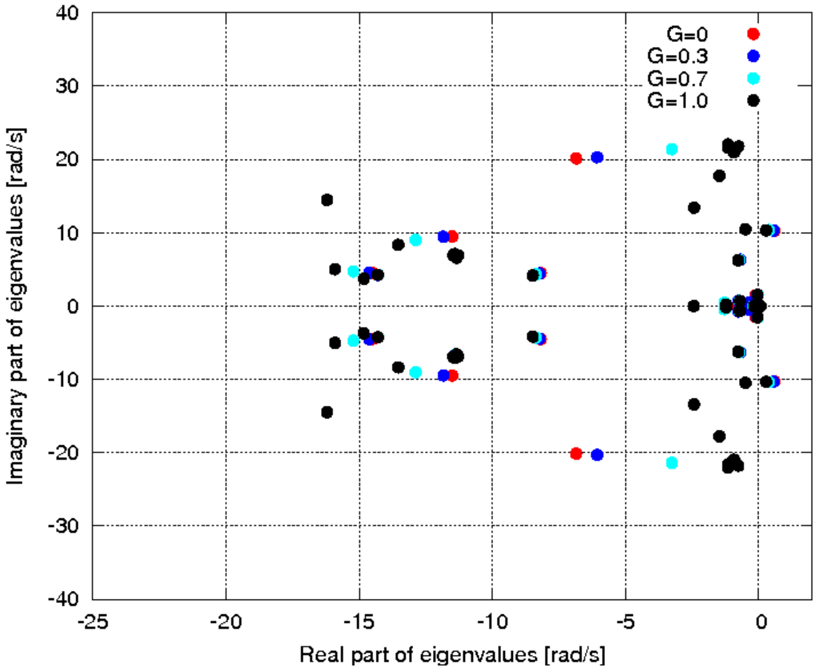

Figure 7: Root loci for complete helicopter model in forward flight.

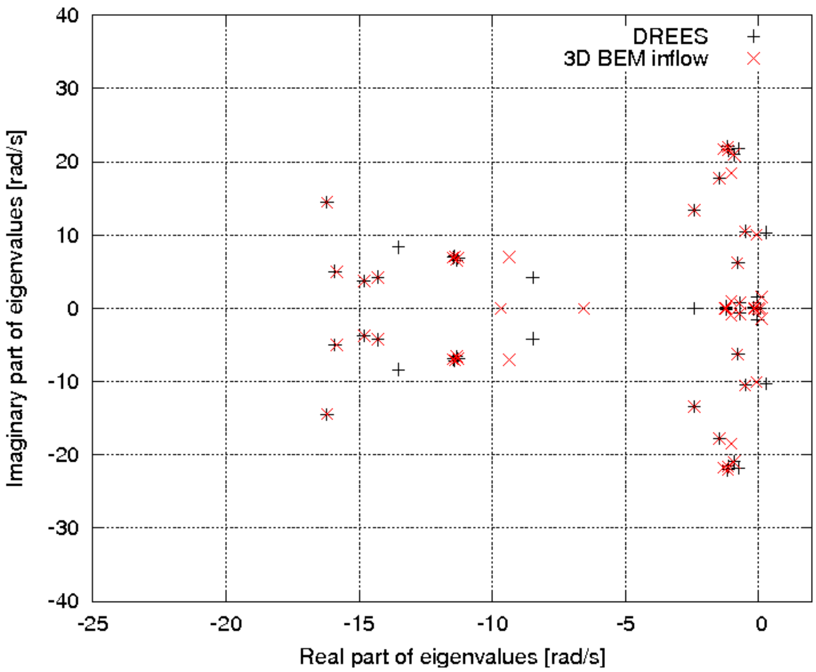

Figure 8: Influence of different inflow models.

- there appears to be a slight dependence on the airspeed, since high speed instability occurs at lower pilot gains compared to hover.

Foreseen investigation will feature more detailed pilot dynamics models, to address the sensitivity of the phenomenon to accurate human arm kinematic and dynamic properties, and the identification of viable design criteria to decouple the pilot from the aeroelasticity of the vehicle, in order to provide guidelines for the reduction of the proneness of new and existing helicopter designs to this type of dynamic instability.

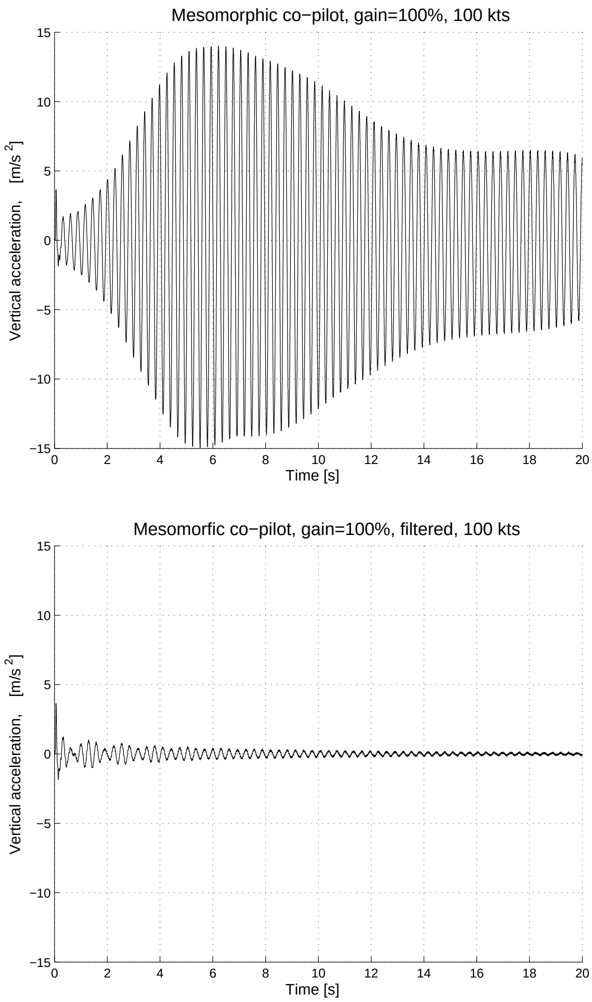

Figure 9: Influence of the notch filter on the vertical acceleration.

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