POLITECNICO MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE
E DELL'INFORMAZIONE

Executive Summary of the Thesis

Towards Robust Stability Design for Rotorcraft-Pilot-Coupling: Pilot Modeling and Sensitivity Analysis

Laurea Magistrale in Aeronautical Engineering - Ingegneria Aeronautica

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Academic year: 2021-2022

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1. Introduction

,Rotorcraft are an harsh environment due to vibrations of different nature in which the pilot has to perform tracking tasks or specific maneuvers coping with the associated workload of different stress levels. These vibrations can be the origin of misleading cues and worsen the pilot's situational awareness, giving rise to an adverse interaction between the pilot and the helicopter. The pilot is induced to inject back those vibrations in the rotorcraft's control inceptors through the Biodynamic-Feedthrough (BDFT) response of the pilot, eventually leading to dangerous or destructive situations. This adverse interaction is called the Rotorcraft-Pilot-Coupling (RPC) and concerns the involuntary pilot response to the vibrational inputs that falls in the frequency range of 2-8 Hz (Ref.[1]), together with the helicopter's structural modes. Thus a *bio-aeroelastic* analysis is necessary.

Although the BDFT pilot response refers to all directions in space, hereafter the focus is on the so called "vertical bounce" phenomena. The vertical dynamics involves the collective inceptor dynamics, through which the pilot controls the helicopter thrust by changing the blades' pitch angle by the same amount, and the dynamics of the pilot's left arm, linked to the collective lever. This dynamics is considered more prone to RPC since a change in collective pitch control results in an immediate change in thrust force, while changes in cyclic pitch control induce pitch or roll moments, usually filtered by the low-pass characteristics of the main rotor.

The aim of this thesis work is to propose analytical pilot models to be coupled with a simplified helicopter model in order to perform a stability sensitivity analysis by changing a specific set of parameters related to the pilot-lever system. The proposed pilot models are based on the modal characteristics (ω_i, ξ_i) of a more complex multibody model, that are used to describe the pilot's dynamics. In particular, these models are used as "semi" grey-box models, as explained in the following.

This work proceeds as follows: in section 2 the helicopter model is described along with all the related simplifying assumptions. The proposed pilot models are reported in section 3, where the modal identification procedure performed to capture the vertical pilot left arm dynamics from the multibody model response, is described. Once the models are set, the closed loop system is built in section 4 followed by the sensitivity analysis and models comparison in section 5. Moreover, the effects of a demanding flight condition is taken into account by changing the limbs muscles impedance caused by the central nervous system, analytically introduced in the multibody model through the Torque-Less Activation Modes (TLAMs).

2. Helicopter Model

The proposed helicopter model used for the vertical bounce investigation consists of the airframe vertical motion (z) and the main rotor collective flap angle (β), generally induced by a change in collective blades' pitch angle ($\Delta\delta$).
The model comprises rigid, articulated blades whose degrees of freedom are restricted to only flapping, with no hinge offset. The simplified model neglects details of the rotor hub geometry and kinematics, the drive train dynamics and rotor aerodynamics details such as inflow, twist or tip losses.
The aerodynamic model is based on the blade element momentum theory where no interaction between airfoils is considered. The inertia and aerodynamic forces are related by the Lock number defined as $\gamma = (\rho ac R^4)/I_\beta$ where ρ is the air density, a is the lift curve slope (set to 2π), c is the airfoil chord, R is the rotor radius and I_β is the flap inertia moment.
The flapping degree of freedom is essential to correctly describe the vertical dynamics since it introduces an elastic mode, typically well damped ($\xi_\beta >> 50\%$) with natural frequency (ω_β) that belongs to the frequency range of interest, especially for medium-high weight rotorcraft (Ref.[2]). Furthermore, when considering take-off or landing maneuvers on a horizontal flat ground, the main rotor trim is essentially characterized by axial flow conditions where the proposed analytical model can correctly represent the analyzed configuration. Indeed, the model can eventually consider the landing gear's dynamics contribution. Considering a trim condition, the resulting linearized equations of motion in matrix form are:

$$\mathbf{M}_h \Delta\ddot{\mathbf{x}} + \mathbf{C}_h \Delta\dot{\mathbf{x}} + \mathbf{K}_h \Delta\mathbf{x} = \mathbf{F}_h \Delta\delta \qquad (1)$$

where $\mathbf{\Delta x} = [\Delta z, \Delta\beta]^T$. The landing gear's contribution appears in the vertical dynamics with the terms $c_{lg}\Delta\dot{z}$ and $k_{lg}\Delta z$, where $c_{lg} = 2m_h\xi_h\omega_n$ and $k_{lg} = m_h\omega_n^2$, being $\xi_h = 0.06$ and $\omega_n = 1.3$Hz the landing gear's damping ratio and natural frequency. The pitch-flap coupling is involved in the dimensionless flap frequency $\hat{\nu}_\beta$ in the $\mathbf{K}_h$ matrix with a term proportional to $\Delta\beta$. Both equations have as input the change of blades collective pitch ($\Delta\delta$) through matrix $\mathbf{F}_h$. The system is then cast into state-space (SS) form, where the output is the vertical airframe acceleration ($\Delta\ddot{z}$) so that the Single-Input-Single-Output (SISO) helicopter system in frequency domain reads:

$$\Delta\ddot{z} = H_{\ddot{z}\delta}(s)\Delta\delta \qquad (2)$$

This simplified model is able to capture the vertical bounce in hover condition. However, it is not conservative in forward flight, where the vertical motion is strongly coupled with the longitudinal and lateral-directional dynamics.
Three different articulated rotor helicopter data are proposed (Tab.[1]) to perform the sensitivity analysis from different helicopter perspectives. The three models are named as Helicopter A, B and C, where Helicopter B refers to the CH-53 helicopter data and the helicopter C refers to the SA330 data. Helicopter A name can not be reported due to confidentiality reasons.

	Symbol	A	B	C
Mass	m_h [kg]	12000	15227	7537
Number of Blades	N_b [-]	5	6	4
Rotor Radius	R [m]	9.50	11.01	8.18
Rotor Speed	Ω [rpm]	205.0	184.2	258.0
Lock Number	γ [-]	10.7	12.4	8.2
Flap Static Moment	S_β [kg m]	650.0	819.0	385.7
Flap Inertia Moment	$I_\beta [kg\ m^2]$	3800.0	5489.0	2052.1
Flap Frequency	ν_β [-]	1.040	1.048	1.035
Pitch-Flap Coupling	δ_3 [deg]	15	0	0

Table 1: Helicopter Data

The flapping frequencies are $\omega_{\beta A} = 3.47$[Hz], $\omega_{\beta B} = 2.18$[Hz] and $\omega_{\beta C} = 3.93$[Hz], highlighting that the flapping dynamics belongs to the same bandwidth of the pilot involuntary response.

3. Pilot Model

The purpose of the simplified pilot models is to represent the pilot left arm motion, subject to vertical vibrations, through analytical expressions. Two models are proposed: a two degrees of freedom (2DOF) pilot model and a one degree of freedom (1DOF) pilot model, both based on the response of a more complex multibody model.
The multibody model comprises the modeling of the complete pilot's upper-body, control inceptors and seat, referring to an helicopter cockpit geometry (Ref.[6]). The model dynamic analysis is performed in the MBDyn (www.mbdyn.org) software environment. The eigenanalysis provides the natural frequency (ω_i) and the damping ratio

(ξ_i) of each mode, along with the eigenvectors. The modal shapes can be visualized in the Blender free-software, through which the two modes that involve the left-arm motion are extracted. The modal analyses are performed by changing the mass (m_l), the spring stiffness (k_l) and the reference angle (θ_0) of the collective lever by factors of $M_f = K_f = [0, 50, 100]\%$ of the nominal values and $\theta_{\%} = [20, 35, 50, 75, 90]\%$ of the complete lever range $\Delta\theta = 30$ deg, corresponding to the absolute angle values of $\theta_0 = \theta_{min} + \Delta\theta \cdot \theta_{\%}/100$, with $\theta_{min} = 15$ deg. The lever friction coefficient is set to zero ($c_l = 0\%$), thus considering a frictionless hinge.
Two modal shapes that concern the left arm motion are identified among the computed modes. They mainly involve the hand and the elbow nodes motion, differing in their relative phase: one is an in-phase mode (**IPM**) and the other one is an out-of-phase mode (**OPM**).
While changing the θ_0 numerical values, the Modes Assurance Criteria is applied in order to track the eigenvectors so that data are correctly extracted.

The 2DOF pilot model is composed of two mass-damper-spring systems, representing the hand and elbow mass dynamics. The two masses are connected to each other through the forearm, whose rigid dynamics is neglected.

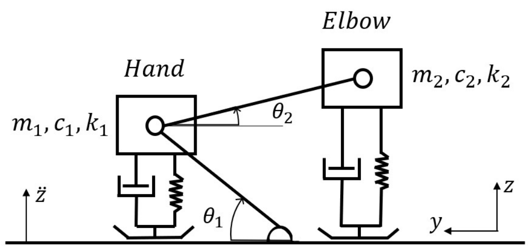

Figure 1: Pilot Model : 2 DOF

The collective lever is a rigid body with mass, length, CG position and resulting inertia. The lever has an additional damper (C_l) for friction and a balancing spring (K_l).
The linearized equations of motion are reported in matrix form for conciseness:

$$\mathbf{M}_p\Delta\ddot{\theta} + \mathbf{C}_p\Delta\dot{\theta} + \mathbf{K}_p\Delta\theta = \mathbf{F}_p\Delta\ddot{z} \quad (3)$$

where $\mathbf{M}_p, \mathbf{C}_p, \mathbf{K}_p$ are the mass, damping and stiffness matrices of the system, $\boldsymbol{\Delta\theta} = [\Delta\theta_1, \Delta\theta_2]^T$ is the unknown vector and $\boldsymbol{\Delta\ddot{z}}$ is the acceleration input. The linearization depends on both θ_{01} and θ_{02}, where the latter is the absolute reference angle of the forearm, that linearly depends on θ_{01}: $\theta_{02} = -0.78\theta_{01} + 65.21$. To exploit the system in modal form, the modal base must be computed. The unknown vector is written as $\boldsymbol{\Delta\theta} = \mathbf{Vq}$ where $\mathbf{V}$ is the eigenvector matrix and $\mathbf{q}$ is the new unknown vector. Substituting $\boldsymbol{\Delta\theta}$ in Eq.[3] and pre-multiplying by $\mathbf{V}^T$, the equations read:

$$\ddot{\boldsymbol{q}} + \boldsymbol{C}\dot{\boldsymbol{q}} + \boldsymbol{K}\boldsymbol{q} = \boldsymbol{F}\ddot{\boldsymbol{z}} \quad (4)$$

where $\mathbf{F} = \mathbf{V}^T\mathbf{F}_p$, $\mathbf{C} = diag[2\xi_i\omega_i]$ and $\mathbf{K} = diag[\omega_i^2]$ with i = 1,2. The modal mass matrix is the identity matrix since eigenvectors are computed with the unit mass normalization. The eigenanalysis is performed by only considering matrices $\mathbf{M}_p$ and $\mathbf{K}_p$ that depend on m_1, m_2, k_1, k_2 that are not known a priori. They are estimated such that the error between the MBDyn trend of the eigenvalues and the actual mathematical expression of the eigenvalues of the 2DOF model in which the parameters are involved, is minimized. The equations are then casted into SS form, imposing $\Delta\theta_1$ as the output.
The whole procedure justifies the name of "semi" grey box model, since the process is driven by ω_i and ξ_i computed in MBDyn, while the input ($\mathbf{B}_{ss}$) and output ($\mathbf{C}_{ss}$) matrices of the SS form are computed with their analytical expressions.

The 1DOF model is the simplified version of the 2DOF model, involving only one oscillatory behavior by neglecting the elbow's dynamics, based on the Mayo's model used in Ref.[3]. The corresponding equation of motion can be written in modal terms as follows:

$$H_{\theta\ddot{z}}(s) = -\hat{K} \cdot \frac{1}{s^2 + 2\hat{\xi}_{pe}\hat{\omega}_{pe}s + \hat{\omega}_{pe}^2}$$

where the explicit expressions for $\hat{\omega}_{pe}$, $\hat{\xi}_{pe}$ and $\hat{K}$ are:

$$\hat{\omega}_{pe} = \sqrt{\frac{\omega_{pe}^2 + (K_l - S_l g \sin\theta_0)/(m_p l^2)}{1 + J_l/(m_p l^2)}}$$

$$\hat{\xi}_{pe} = \frac{1}{2}\frac{2\xi_{pe}\omega_{pe} + C_l/(m_p l^2)}{\sqrt{((1 + J_l/(m_p l^2))(\omega_{pe}^2 + (K_l - S_l g \sin\theta_0)/(m_p l^2))}}$$

$$\hat{K} = \frac{\cos\theta_0}{l}\frac{1 + S_l/(m_p l)}{1 + J_l/(m_p l^2)}$$

where $\omega_{pe} = \sqrt{k_p/m_p} \cdot \cos\theta_0$ and $\xi_{pe} = c_p/(2\sqrt{m_p \cdot k_p}) \cdot \cos\theta_0$, highlighting the separated

contribution of the pilot (ω_{pe}, ξ_{pe}) and of the lever to $\hat{\omega}_{pe}$ and $\hat{\xi}_{pe}$. In these expressions the value of the pilot modal mass (m_p) is needed. Unfortunately, no data or procedures to find its value are present in the literature. The modal mass is roughly estimated by imposing a force gradient of $1K_{gf}/deg$, considering static reference conditions.
In the following, ω_{pe} and ξ_{pe} are replaced by the OPM's natural frequency and damping ratio computed with $M_f = K_f = 0\%$, while the lever contribution to $\hat{\omega}_{pe}$ and $\hat{\xi}_{pe}$ is analytically added using the above equations. This allows to overcome the 2DOF model limitations in the parametric analysis: lever parameters influence the ω_i and ξ_i values computed in MBDyn. The parametric analysis, using the 2DOF pilot model, can be then performed with values within the MBDyn analyzed percentages ranges. In fact, by changing a posteriori the lever parameters in the analytical model would affect the input matrix $\mathbf{F}_p$ and not the ω_i and ξ_i, leading to a physical mismatch between the analytical model and the actual pilot response. Reference values for both the models are reported in Tab.[2]:

Pilot	Symbol	2DOF	1DOF
Natural frequency (1)	ω_1[Hz]	1.68	1.68
Damping ratio(1)	ξ_1 [%]	44	44
Natural frequency (2)	ω_2 [Hz]	2.85	-
Damping ratio (2)	ξ_2 [%]	22	-
Forearm length	l_a [m]	0.35	-
Modal Mass	m_p [kg]	-	4
Lever			
Reference Collective Angle	θ_0 [%]	20	20
Static moment	S_l [kg m]	0.04	0.04
Lever length	l [m]	0.35	0.35
Lever mass	m_l [kg]	0.315	0.315
CG position	x_{CG} [m]	0.1275	0.1275
Angular spring	K_l $[N \cdot m/rad]$	15	15
Angular damper	C_l $[N \cdot m/rad/s]$	0	3

Table 2: Pilot Model : Reference Parameters

Finally, both the pilot models can be cast into SISO form in frequency domain as:

$$\Delta\theta = H_{\theta\ddot{z}}(s)\Delta\ddot{z} \qquad (5)$$

The difference between the 1DOF and the 2DOF pilot models is basically in the number of states involved in the system dynamics, being the input ($\Delta\ddot{z}$) and the output ($\Delta\theta$) the same.

4. Rotorcraft Pilot Coupling

Once the analytical models are defined for both pilot and rotorcraft, the coupled system can be analyzed. The contribution of the pilot to the collective lever rotation can be divided into two parts: the involuntary contribution $\Delta\theta$ and the voluntary contribution $\Delta\theta^*$ that can be modeled in several ways (Ref.[4]). Considering both terms in the feedback-loop, the equation reads:

$$(1 - G_0 H_{\theta\ddot{z}}(s) H_{\ddot{z}\delta}(s))\Delta\ddot{z} = G_0 H_{\ddot{z}\delta}(s)\Delta\theta^*$$

where G_0 is the gear ratio, that takes into account the mechanical transmission between the change in lever angle and the actual change in blades collective pitch angle, namely $\Delta\delta = G_0\Delta\theta$. The closed-loop transfer function (TF) is thus the coefficient of $\Delta\ddot{z}$ minus 1:

$$H_{RPC} = -G_0 H_{\theta\ddot{z}}(s) H_{\ddot{z}\delta}(s)$$

The closed-loop system stability analysis is performed through the robust approach by mean of the gain (g_m) and phase (ϕ_m) margins, graphically represented by the Nyquist diagrams. Typically, the system is considered robustly stable if $g_m > 6$dB and $\phi_m > 45$ deg.

5. Results

Once the systems are coupled, the stability sensitivity analyses using both the pilot models are performed: firstly, in order to assess the parameters that mainly affect the stability margins, a preliminary parametric analysis is needed. Consequently, in the full factorial design (FFD) analysis a subset of parameters are free to change simultaneously, so that qualitative design criteria can be assessed to avoid RPC occurrences. The closed loop system analyses are performed in hovering flight condition.

The values changed for the 2DOF pilot model are θ_0, ω_1, ξ_1, ω_2 and ξ_2. By changing θ_0, a non-monotonic trend of the gain margin is observed: with increasing θ_0 the gain margin decreases, then increases again (Fig.[2]).
When ω_1 and ξ_1 are changed independently, no relevant changes in stability margins are observed. In fact, by checking the observability matrix rank of the 2DOF model in SS form, it is confirmed that the IPM is not seen by the output, being the rank equal to 2. The more general sensitivity analysis can be performed with the 1DOF pilot model, by letting all the parameters related to the model in Tab.[2] change, where the OPM characteristics are used, based on the previous observability check. In particular, by changing θ_0, with the 1DOF

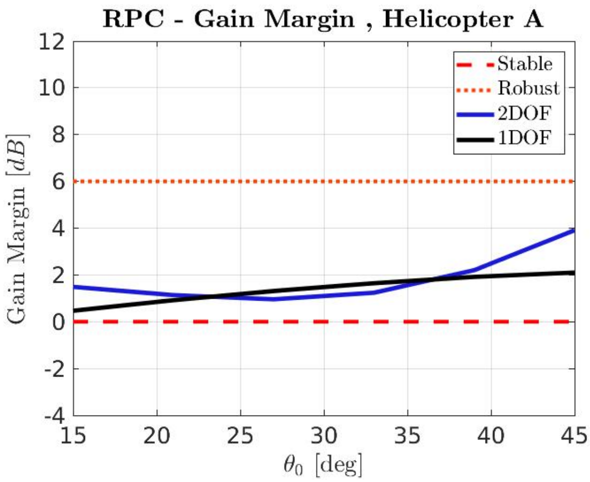

Figure 2: Sens. Analysis : 2 DOF VS 1DOF , θ_0

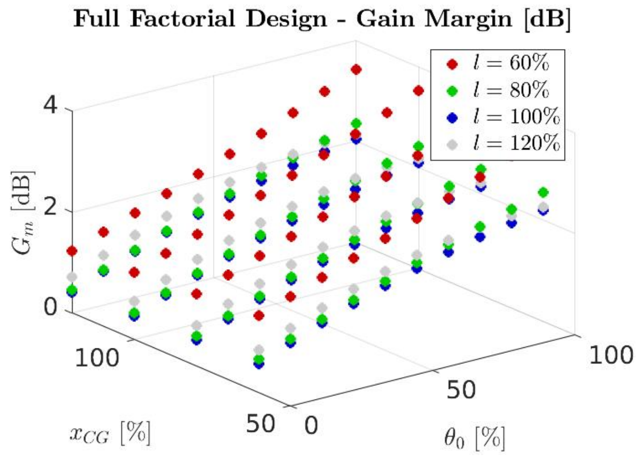

Figure 4: FFD : Gain Margin , Lever Length

model the g_m trend is monotonic with increasing θ_0 (Fig.[2]). The pilot-lever values which are affecting the stability the most are the x_{CG}, m_l, l and θ_0, highlighting that a proper lever design is crucial to avoid the RPC phenomena. Stability margins are further studied in the FFD, by changing the parameters cited above.

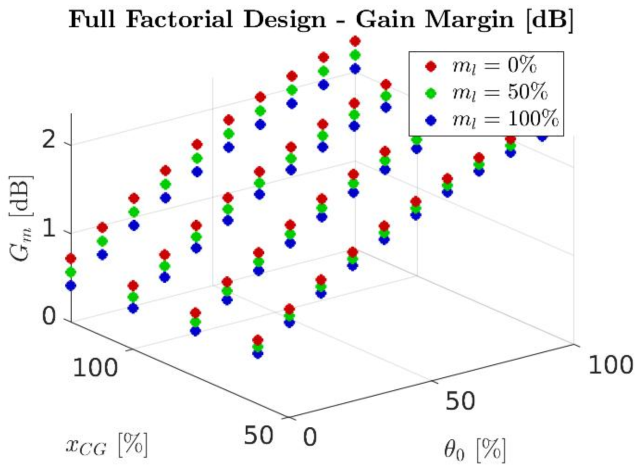

Figure 3: FFD : Gain Margin , Lever Mass

The FFD study confirms the sensitivity analysis trends; moving x_{CG} towards the pivot point increases the stability and increasing θ_0 raises the gain margin, regardless the lever mass and length. By increasing the lever mass, g_m reduces since $\omega_l \propto \sqrt{(K_l/J_l)}$, decreasing the lever contribution to the overall natural frequency (Fig.[3]). The lever length effects on g_m are not as linear as the one in Fig.[3]. In particular, different slope trends occur with increasing θ_0 for different l, as shown in (Fig.[4]).

The Bode diagrams of the 2DOF and 1DOF pilot models are then compared with the frequency response function of a grey-box pilot model whose parameters are identified from the input-output (IO) data of an on-going test campaign at Politecnico di Milano, DAER, on the FRAME-Sim testbed (Ref.[5]). This model is composed of the voluntary pilot response, described by a real pole and zero, and of the involuntary response described by a couple of complex-conjugate poles. The analytical models mainly differ from the grey-box model for the static gain value of nearly $\Delta K_s = 50\%$, while the dynamic response is well described, with differences in the oscillatory response of $\Delta\omega_n = 25.5\%$ and $\Delta\xi_n = 46.1\%$. However, it is meaningful to compare the closed-loop system behaviour between the 2DOF pilot model and the grey-box pilot for changing θ_0. The coupling is performed with the data of Helicopter A (Fig.[5]) and B (Fig.[6]). The already observed trend in Fig.[2] is qualitatively reproduced by the grey-box pilot model. This is a remarkable result since it allows to understand which modal contributions are involved in the actual pilot response. In fact, from the IO data it is not possible to explicitly observe the IPM mode *dissipative* contribution (for low θ_0) since the response is a 1DOF-like response where only the OPM is observed. So far, no evidences of this modal contribution is mentioned in the literature, to the author's knowledge.
The landing/take-off maneuver is investigated by considering the contribution of the landing gear dynamics in the helicopter equations. The 1DOF model is coupled with all the three helicopters, comparing the hovering flight condition with the landing/take-off maneuver. The main effect of the

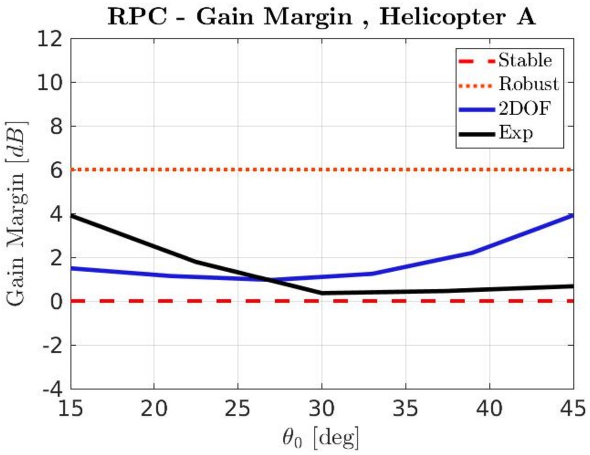

Figure 5: Sens. Analysis : 2DOF VS Exp , θ_0

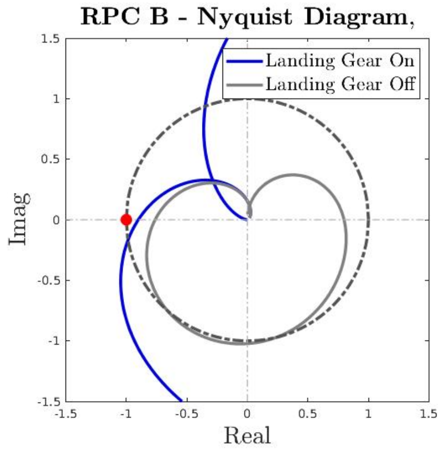

Figure 7: RPC with Landing Gear - Nyquist Plot

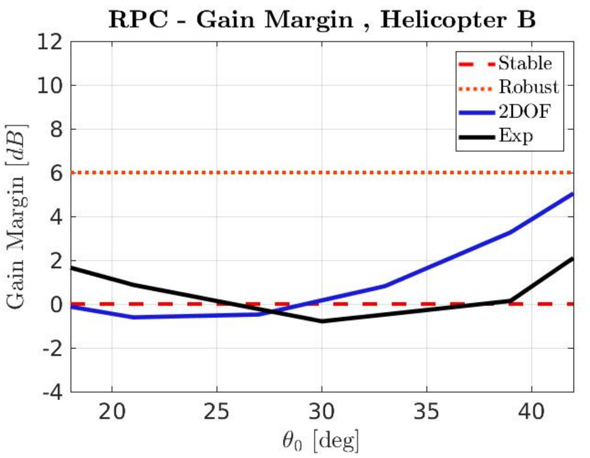

Figure 6: Sens. Analysis : 2DOF VS Exp , θ_0

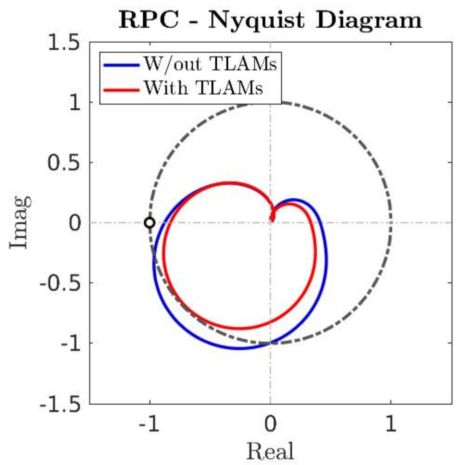

Figure 8: RPC with TLAMs: Nyquist Plot

landing gear dynamics is to introduce a significant phase lag. The major change in stability margins are encountered for the heaviest helicopter (B), with a decrease in margins of $\Delta g_m = -165.35\%$ and $\Delta\phi_m = -142.35\%$ with respect to hovering (Fig.[7]). Finally, the effect of a demanding flight condition is taken into account, changing the muscles impedance by introducing the TLAMs effects. The change in muscles stiffening is reflected in an increase of ω_1 and ω_2 values, while no specific pattern is observed for ξ_1 and ξ_2. The effect on stability is to increase the gain margin of $\Delta g_m = 42.6\%$ while the phase margin goes from $\phi_m = 15.98$ deg to $\phi_m = +\infty$ (Fig.[8]). Unfortunately, relating the specific flight condition to the corresponding muscle stiffening is not straightforward and would require a specific study.

6. Conclusions

This thesis work discussed an analytical pilot modeling approach to investigate the Rotorcraft-Pilot-Coupling phenomena known as vertical bounce. The proposed 2DOF pilot model shows good qualitative agreement with the experimental data when coupled with the same helicopter model, since both the identified modes from MBDyn are involved in the modeling, giving an important insight in the understanding of the actual pilot BDFT response. The comparison between the 1DOF and the 2DOF pilot model underlines a discrepancy in stability margins for low reference angles due to the neglected IPM contribution in the 1DOF model. The FFD provides ranges of x_{CG}, m_l, l and θ_0 for which significant loss of stability occurs. The effects on stability of the landing/take-off maneuver is considered, where the heaviest helicopter (B) appears to be more prone to vertical bounce especially due to a decrease in phase margin of $\Delta\phi_m = -38.9$ deg.

Finally, the muscle impedance change is considered by analytically introducing the TLAMs effects. The overall stability is increased in both gain and phase margins, physically corresponding to a more focused pilot that quickly reacts to changes in collective angle.

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