A Rotorcraft Conceptual Design Tool for Handling Qualities Evaluation

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Abstract

The present work aims at laying the foundations for a design tool able to include the study of handling qualities during the rotorcraft conceptual design. In particular, results from NDARC conceptual design software are employed to build a flight mechanics model augmented with a control system. Evaluation of handling qualities is done relatively to the sized rotorcraft in order to influence the rotorcraft re-design until imposed requirements are met. The design tool is implemented into a general and versatile environment, able to account for different rotorcraft architectures and to host innovative features. An example is the automatic generation of the rotorcraft model meant for coupling the conceptual design tool with a flight simulator in support of the evaluation of handling qualities.

NOTATION

ϕ, θ	Euler angles for roll and pitch
θ_0, θ_{0T}	Main rotor and tail rotor collective pitch
θ_{1s}, θ_{1c}	Longitudinal and lateral cyclic pitch
g	Gravity acceleration
I_{xx}, I_{yy}, I_{zz}	Roll, pitch and yaw moments of inertia
I_{xz}	Roll and yaw product of inertia
L, M, N	Body axis roll, pitch and yaw moments
Lf, Mf	Longitudinal and lateral rotor flapping moments
m	Rotorcraft mass
p, q, r	Roll, pitch and yaw angular rates
u, v, w	Longitudinal, lateral and vertical velocities
U_e, V_e, W_e	Longitudinal, lateral and vertical trim velocities
X, Y, Z	Body axis longitudinal, lateral and vertical forces
β_{1c}, β_{1s}	Longitudinal and lateral flapping angles
Φ_e, Θ_e	Trim Euler angles for roll and pitch

$$L'_p = \frac{I_{zz}}{I_{xx}I_{zz}-I_{xz}^2} L_p + \frac{I_{xz}}{I_{xx}I_{zz}-I_{xz}^2} N_p$$

$$N'_r = \frac{I_{xz}}{I_{xx}I_{zz}-I_{xz}^2} L_r + \frac{I_{xx}}{I_{xx}I_{zz}-I_{xz}^2} N_r$$

I. INTRODUCTION

Handling Qualities (HQs) play a fundamental role in rotorcraft design, since they are indicators of how much an aircraft is safe to fly, and how easily pilots can accomplish assigned missions while sparing enough time and attention to fulfill other tasks. HQs are often challenging to assess, in particular for military requirements, and long time may need to be spent during the design and development process fixing HQs issues [1].

Anticipating as mush as possible the evaluation of HQs by taking them into consideration since the very beginning of the design activity could help reducing the number of modifications to be carried out in order to correct unforeseen behavior, which could be the more time and money consuming the later they surface in the process. While such an approach might have been difficult to achieve in the past, today's computational power and well-defined standards offer the possibility to include HQs investigation in multidisciplinary analysis during conceptual and preliminary design.

The challenges of incorporating HQs analyses into conceptual design begin with the fact that conceptual design tools typically do not include the modeling necessary to represent the flight dynamics or a flight control system. Indeed, the lack of detailed modeling at the earliest stages of design could mean to ignore a potentially significant contribution to size, weight and performance estimates for some design activities.

In recent years several aerospace research organizations presented approaches for multidisciplinary design processes in the field of rotorcraft engineering. Among others, worth of mention are the works of DLR [2], NLR [3], Georgia Tech [4], Onera [5] and NASA [6].

Starting from lessons learned in these studies and from suggestions for future developments, a rotorcraft conceptual design tool able to include the study of HQs is suggested in the present work and its general architecture is shown in Fig. 1.

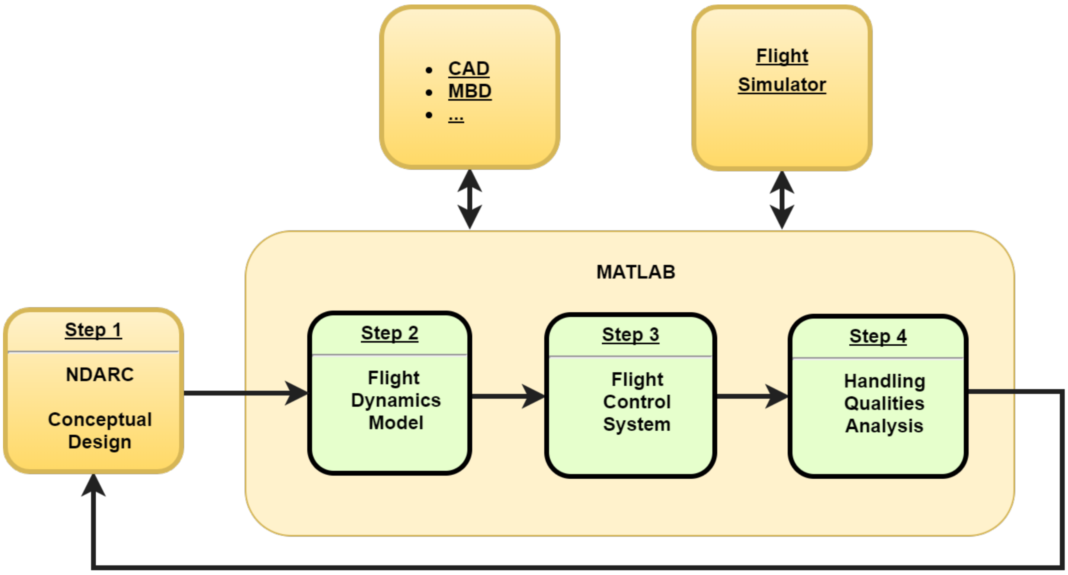


Figure 1: *Rotorcraft conceptual design tool architecture.*

The process includes the following steps:

- Step 1 : Design requirements and rotorcraft description are given as input to a conceptual design software and an initial sizing task is performed.
- Step 2 : Design requirements and output from the conceptual design tool are employed to generate a flight dynamics model of the rotorcraft.
- Step 3 : The flight dynamics model is augmented with a flight control system.
- Step 4 : A HQs analysis is performed relatively to the augmented rotorcraft.

Results from the analysis are then fed back to the conceptual design code in order to influence the re-design. The loop is repeated until desired objectives in terms of HQs and rotorcraft capabilities are accomplished.

The entire methodology has been developed using the software MATLAB which provide a suite of toolboxes to support the required algorithms and models. The tool architecture is general enough to allow hosting data from other analyses (e.g. CAD, Multibody Dynamics, etc.) and communicate with external software. This feature is important in order to acquire additional information which can be determinant in the rotorcraft description and in order to have a versatile instrument able to interchange and compare data from different sources.

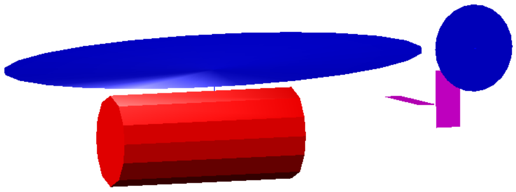
An interesting example is the automatic generation of an output rotorcraft model which is intended for being introduced in a flight simulator. This feature may be extremely important in the early verification of flight dynamics and control systems and could provide the designer with subjective pilot's contributions in HQs definition and assessment.

II. Conceptual Design with NDARC

The loop starts with the conceptual design of a rotorcraft. A conceptual design software is fundamental in the process in order to compare different architectures and to obtain fast results subject to desired requirements. For this step, NDARC code has been employed [7]. NDARC is NASA software for design and analysis of rotorcraft and it performs sizing and analysis tasks starting from an input file containing the description of the rotorcraft in terms of its constituting components and achievable missions and flight conditions.

In the present work, input parameters and reference flight conditions (Tab. 1) for the initial sizing task refer to the Bölkow (now Airbus Helicopters) BO105 helicopter (Fig. 2a). The sized rotorcraft, which is not the actual BO105 but a very similar helicopter belonging to the same class, can be therefore compared with a rotorcraft deeply studied in literature as the BO105. Fig. 2b shows the sketch of the sized BO105 from NDARC conceptual design.

(a) *DLR research helicopter BO105 S123*



(b) *BO105 NDARC sketch*

Figure 2: *Comparison between actual BO105 and BO105 from NDARC conceptual design.*

Table 1: *BO105 sizing missions and flight conditions, Ref. [8].*

Requirement	Value
Max Endurance [min]	210
Max Range [km]	574
Max Speed [km/h]	268
Max Altitude [m]	5180
Max Climb Rate [m/s]	8
Max Climb Rate OEI [m/s]	0.5
Max Take-off Weight [kg]	2400
Hover Altitude OGE [m]	1584
Hover Altitude IGE [m]	2286
Hover Altitude OEI [m]	823

The chosen sizing method is characterized by fixed engine power available and fixed maximum take-off weight while design gross weight, empty weight and main rotor radius are evaluated accordingly starting from an initial guess value.

Tab. 2 shows the comparison between main parameters from actual BO105 and sized BO105.

Table 2: *Results from NDARC initial sizing task.*

Variable	Actual BO105	Sized BO105	Diff. [%]
Aircraft			
Weight Empty [kg]	1256.0	1392.9	+10.9
Design Gross Weight [kg]	2200.0	2024.7	-7.9
Fuel Tank [kg]	400.0	342.1	-14.5
Cruise Drag [m^2]	1.11	1.12	+0.1
Main Rotor			
Radius [m]	4.912	4.671	-4.9
Disk Loading [kg/m^2]	30.37	29.53	-2.8
Design Blade Loading []	0.0660	0.0711	+7.7
Lock Number []	5.09	4.26	-16.3
Tail Rotor			
Disk Loading [kg/m^2]	54.49	56.34	+3.4
Design Blade Loading []	0.0742	0.0770	+3.8

Once the sizing task is complete, the loop is designed to automatically import the results in MATLAB for further elaboration. MATLAB offers a versatile framework and a single interface with external software that may be introduced in the routine in future work and contains useful and already implemented toolboxes for specific types of analysis (e.g. the robust control toolbox).

Importing is done by exploring NDARC's output file to detect the input, output and trim parameters that are needed to build the flight dynamics model. Missing parameters are estimated by using analytical or empirical formulas.

At the same time, the main parameters that describe the rotorcraft at the conceptual design level of fidelity are automatically exported in a text file. This file is used to generate a rotorcraft multibody model that can be imported in the flight simulation facility currently under development at Politecnico di Milano, which is based on a general-purpose multibody simulation, MBDyn [9], for vehicle dynamics, and FlightGear for visualization [10].

III. FLIGHT DYNAMICS MODEL

Data imported in MATLAB from NDARC are used to build the flight dynamics model. The model is currently capable of describing conventional single-main rotor and tail rotor helicopters through a "Hybrid" formulation [11]. The implemented hybrid formulation consists of a 8-DOF flight dynamics model described by a 10-States linear state-space representation:

- 8 states for the 6-DOF rigid body model;
- 2 states for the first order approximation of main rotor flapping equations.

This approach allows in a relatively simple formulation a representation of fuselage-rotor couplings that a 6-DOF model alone cannot capture. Furthermore, this formulation allows to model multiple rotors by considering just two states for each rotor, avoiding adding too much complexity to the flight dynamics model.

The linear state-space representation is obtained by linearizing the nonlinear set of equations which represent helicopter motion (Ref. [12]) about a prescribed trim condition. Trim quantities are among variables imported in MATLAB from NDARC, which solves rotorcraft trim for controls and motion that produce aircraft force and moment equilibrium in correspondence to each flight condition and mission segment. For this reason, there is no need to perform trim iterations inside the conceptual design tool, avoiding additional computational costs and guaranteeing consistency between NDARC analysis and the flight dynamics model.

Matrixes and vectors employed in the linear state-space representation are shown in Fig.3.

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u}$$

$$\mathbf{A} = \begin{bmatrix}
\frac{X_u}{m} & \frac{X_v}{m} & \frac{X_w}{m} & 0 & -W_e & \frac{X_r}{m}+V_e & 0 & -g\cos\Theta_e & \frac{X_{\beta_{1c}}}{m} & 0 \\
\frac{Y_u}{m} & \frac{Y_v}{m} & \frac{Y_w}{m} & \frac{Y_p}{m}-W_e & 0 & \frac{Y_r}{m}+U_e & g\cos\Phi_e\cos\Theta_e & -g\sin\Phi_e\sin\Theta_e & 0 & \frac{Y_{\beta_{1s}}}{m} \\
\frac{Z_u}{m} & 0 & \frac{Z_w}{m} & -V_e & \frac{Z_q}{m}+U_e & \frac{Z_r}{m} & -g\sin\Phi_e\cos\Theta_e & -g\cos\Phi_e\sin\Theta_e & 0 & 0 \\
L'_u & L'_v & L'_w & L'_p & L'_q & L'_r & 0 & 0 & 0 & L'_{\beta_{1s}} \\
\frac{M_u}{I_{yy}} & \frac{M_v}{I_{yy}} & \frac{M_w}{I_{yy}} & 0 & \frac{M_q}{I_{yy}} & \frac{M_r}{I_{yy}} & 0 & 0 & \frac{M_{\beta_{1c}}}{I_{yy}} & 0 \\
N'_u & N'_v & N'_w & N'_p & N'_q & N'_r & 0 & 0 & 0 & N'_{\beta_{1s}} \\
0 & 0 & 0 & 1 & \sin\Phi_e\tan\Theta_e & \cos\Phi_e\tan\Theta_e & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & \cos\Theta_e & -\sin\Theta_e & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & Lf_{\beta_{1c}} & Lf_{\beta_{1s}} \\
0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & Mf_{\beta_{1c}} & Mf_{\beta_{1s}}
\end{bmatrix}$$

$$\mathbf{B} = \begin{bmatrix}
0 & 0 & \frac{X_{\theta_0}}{m} & 0 \\
0 & 0 & \frac{Y_{\theta_0}}{m} & \frac{Y_{\theta_{0T}}}{m} \\
\frac{Z_{\theta_{1s}}}{m} & 0 & \frac{Z_{\theta_0}}{m} & 0 \\
0 & 0 & L'_{\theta_0} & L'_{\theta_{0T}} \\
0 & 0 & \frac{M_{\theta_0}}{I_{yy}} & 0 \\
0 & 0 & N'_{\theta_0} & N'_{\theta_{0T}} \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
Lf_{\theta_{1s}} & Lf_{\theta_{1c}} & 0 & 0 \\
Mf_{\theta_{1s}} & Mf_{\theta_{1c}} & 0 & 0
\end{bmatrix} \qquad \mathbf{x} = \begin{Bmatrix} u \\ v \\ w \\ p \\ q \\ r \\ \phi \\ \theta \\ \beta_{1c} \\ \beta_{1s} \end{Bmatrix} \qquad \mathbf{u} = \begin{Bmatrix} \theta_{1s} \\ \theta_{1c} \\ \theta_0 \\ \theta_{0T} \end{Bmatrix}$$

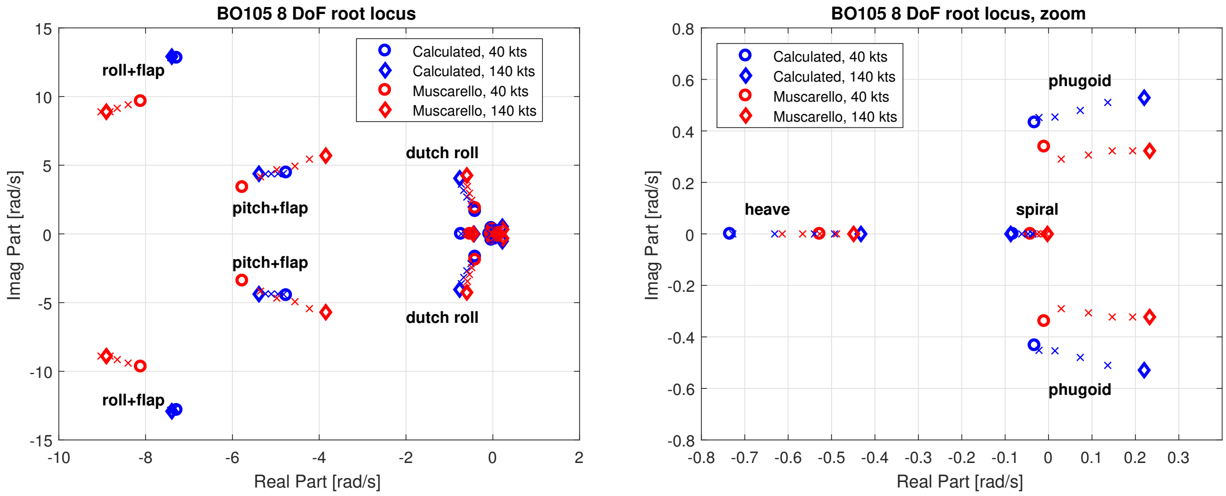
Figure 3: *State matrix* **A***, control matrix* **B***, state vector* **x** *and input vector* **u** *of the linear state-space representation.*

The stability and control derivatives for the equations of motion are obtained from closed-form analytical expressions, taking into account contributions from main rotor, tail rotor, horizontal and vertical tail and fuselage [13].

A set of assumptions is introduced in order to reduce total complexity and computational time. The assumptions produce relatively small errors which are considered acceptable for helicopter conceptual design. In particular, rotor blades are modeled as rigid, linear twisted and untapered. Corrections related to tip losses and root cutouts are taken into consideration. Induced velocity is uniform over the disk while no tip vortex, stall and compressibility effects are considered.

An aspect which requires particular mention is the evaluation of moments of inertia. NDARC does not provide any output regarding mass distribution in the sized rotorcraft. For this reason, moments of inertia have to be calculated during the preliminary computations for stability and control derivatives. Evaluation is performed by considering a uniform mass distribution based on mass, position and geometry of each component. Although not very precise, this approach does not require predictions or partial knowledge of the mass properties for the sized rotorcraft. Future implementation of external software for CAD or tools for geometry generation will allow to more easily predict mass distribution and calculation of moments of inertia.

The flight dynamics model has been validated through time response analyses and poles position. Fig. 4 shows an example of root locus analysis employed for the validation process. The magnitude of the real and imaginary part, as well as the trend with the variation of advancing speed, is generally caught by the model. Considering the fidelity level of sizing data and the simplified hypotheses employed in the present work and taking into account that reference eigenvalues have been evaluated thanks to an aeroelastic helicopter model which is definitely more sophisticated than the one implemented in the tool, obtained results have been judged satisfactory for the present analysis.



(a) *Root locus* **(b)** *Root locus zoom*

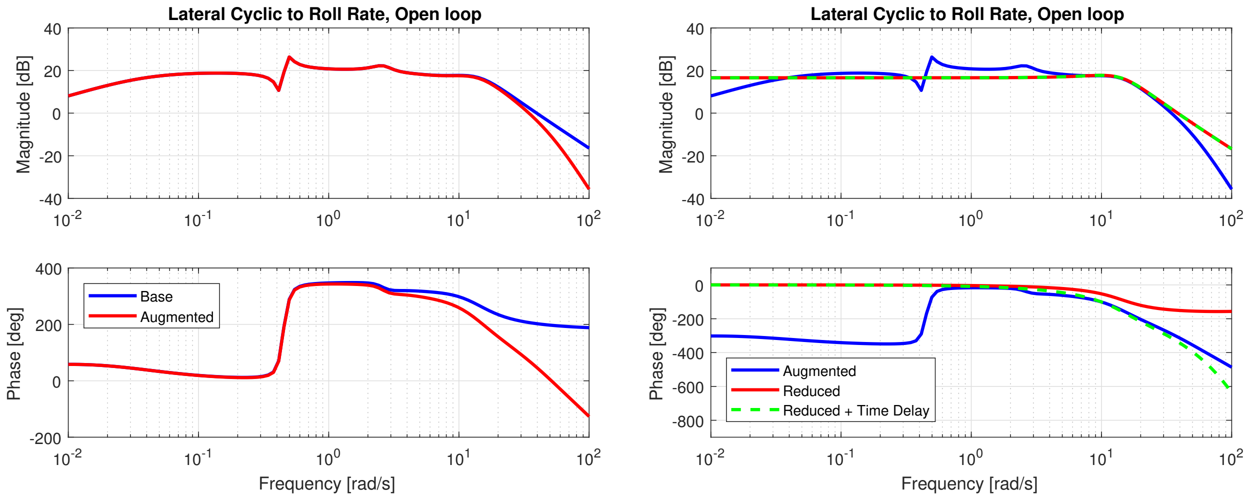
Figure 4: *Root locus comparison between BO105 8-DOF model and Ref. [14].*

IV. Control System Model

The bare airframe model is then augmented with a flight control system in order to make the analysis more general and accurate, since practically all modern rotorcraft include stability augmentation systems. Indeed, many bare-airframe rotorcraft designs are inherently unstable and dynamic response for some architectures is strongly dominated by inter-axes cross-couplings.

In the implemented flight dynamics model inputs are directly specified at the swashplate. However in a rotorcraft under control the control inputs are determined by the regulator and actuated to the swashplate, so actuators are needed. Similarly, the regulator requires that the states are measured or estimated and so sensors have to be placed on the system. Another important aspect is that modern control systems are implemented on digital computers and so system time delays due to signal transport, processing and filtering have to be taken into consideration. All these delays can be coalesced into an equivalent pure time delay. Both actuators and sensors hold their own dynamics and this is taken into consideration when modeling the system by cascading them respectively upstream the inputs and downstream the outputs of the bare airframe model (Fig. 5a).

In order to cope with low order models for the regulator synthesis and for a better physical insight into the aircraft attitude response, the augmented model is simplified. Thanks to a modal decomposition process, the bare-airframe model is decoupled into two 2-order single-axis models representative of rotorcraft longitudinal and lateral dynamics in the frequency range $1-10\ rad/s$. Subsequently, an equivalent pure time delay is introduced in the reduced models in order to



(a) *Augmented model* **(b)** *Reduced model*

Figure 5: *Bode Plot for flight dynamics reduced models on roll axis.*

match the phase behavior of the augmented model, Fig. 5b).

The main requirement to implement a control law at the conceptual design level is an architecture general enough to deal with a variety of vehicle configurations and widely varying characteristics since the model description is uncertain by definition, referring to a not yet existing aircraft. Furthermore, many requirements in terms of rotorcraft response capabilities and standards have to be taken into account during the synthesis of the regulator. For all these reasons, the regulator is synthesized among the H_∞ framework, [15].

The H_∞ approach is a modern control technique suitable for MIMO systems and for dealing with uncertain parameters and many requirements. In particular, a structured H_∞ method is implemented in order to impose the structure of the control law architecture a priori, obtaining low order regulators instead of fully coupled transfer matrices. Control laws requirements are encoded into frequency dependent weights for performance, control action moderation, robustness and safety. Weights are imposed on the closed-loop sensitivity functions. In particular:

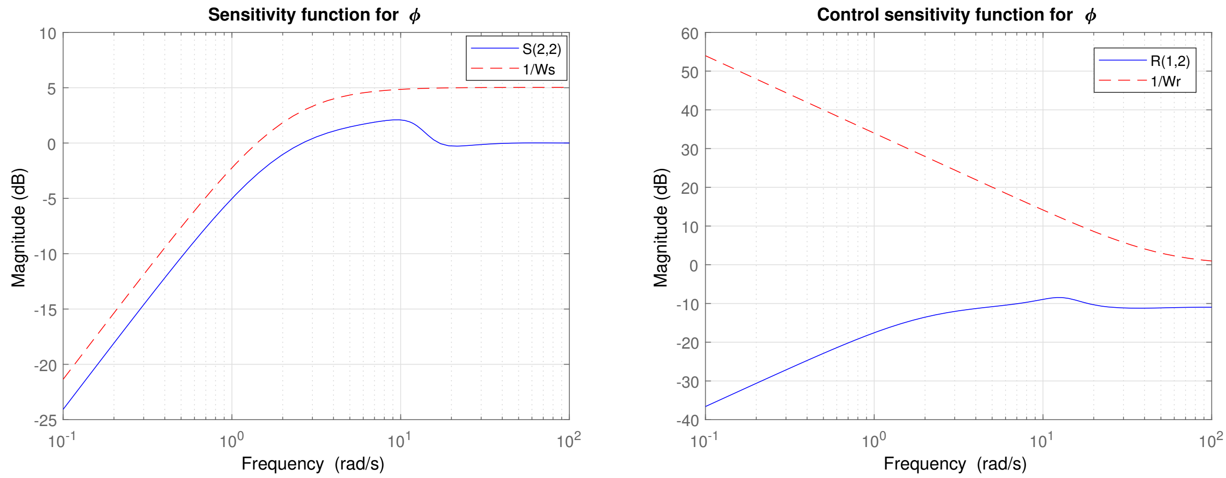
- Performance requirements (such as bandwidth and damping ratio) are addressed by imposing weights on the sensitivity function. The sensitivity function can be interpreted as the closed-loop transfer function from reference signal to tracking error or from disturbance on the output to the output itself. At low frequency, the magnitude of the sensitivity function is small due to large loop transfer function gain, meaning that the tracking error is kept small or the disturbances are rejected (Fig. 6a);
- Control action moderation requirements are addressed by imposing weights on the control sensitivity function. The control sensitivity function can be interpreted as the transfer function from reference signal to control action, the transfer function from disturbance on the output to control action, the transfer function from measurement noise to control action. In all these cases, it is desirable to keep the magnitude of the control sensitivity frequency response as small as possible outside the bandwidth of the system (Fig. 6b);
- Robustness with respect to uncertainty is addressed by imposing a frequency representation of model uncertainty as a weight on the complementary sensitivity function. The magnitude of the weight on the complementary sensitivity function represents the amount of relative uncertainty of the perturbed model with respect to the nominal one as a function of frequency.

Robustness requirements need particular mention, since conceptual design quantities show a high degree of uncertainty. Indeed, robustness requirements are needed to guarantee the stability of the closed-loop system during the optimization process [16].

Fig. 7a shows an example of weight choice for robustness requirements in case of uncertain moment of inertia values. Indeed, moments of inertia are not computed by NDARC and, without a CAD model as in this case, an estimate of their values is necessary to obtain the flight dynamics model. Uncertainty on their values is thus taken into consideration in the present analysis by applying $\pm 10\%$ uncertainty on roll and pitch moments of inertia.

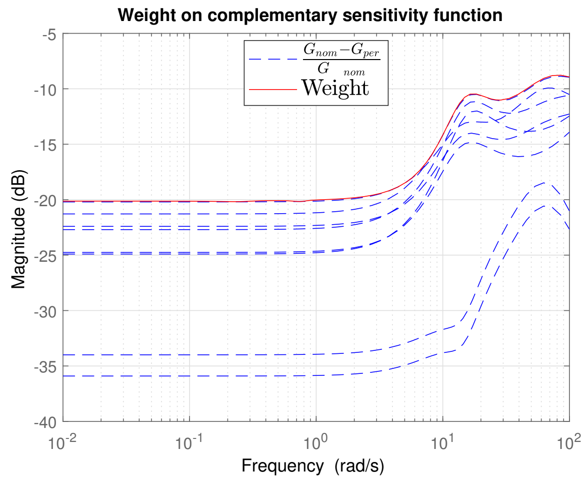
V. Handling Qualities Assessment

The final step of the loop consists in a HQs assessment procedure. HQs analysis is performed by applying bandwidth and phase delay requirement from Aeronautical Design Standards, ADS-33E-PRF [17]. ADS-33 supports HQs investi-



(a) *Sensitivity function* **(b)** *Control sensitivity function*

Figure 6: *Sensitivity and control sensitivity functions from regulator synthesis.*



(a) *Complementary sensitivity function weight*

Figure 7: *Weights on sensitivity functions for regulator synthesis.*

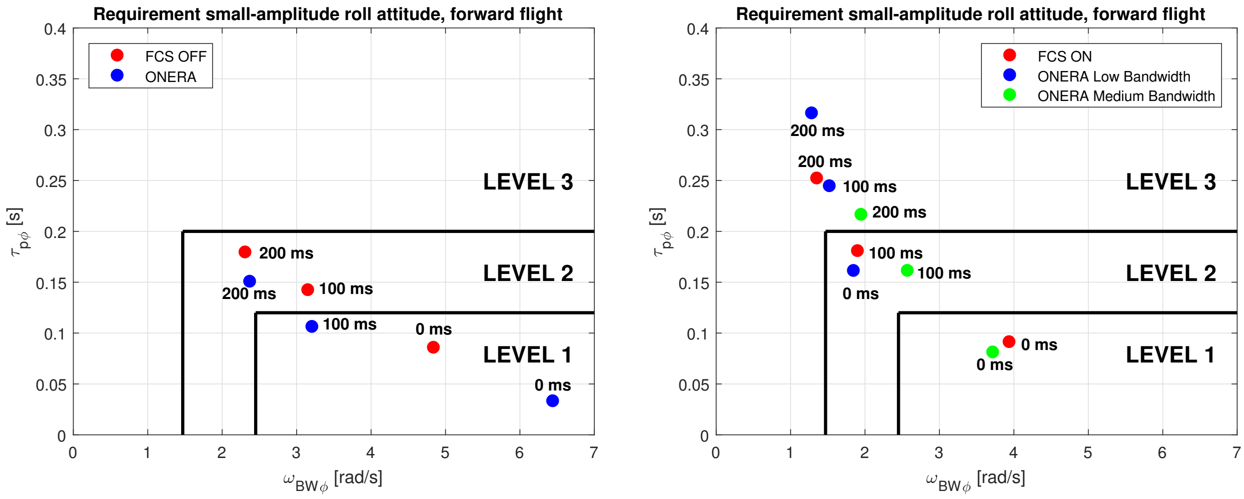
gation through a mission-oriented approach based on mission task elements performed with different usable visual cue environments.

Bandwidth and phase delay requirement is implemented for the analysis of small-amplitude roll attitude changes in forward flight and is related to the aircraft's ability to perform small amplitude tasks such as closed loop compensatory tracking. The main reason for this choice is the intention to focus the attention on a criterion compliant with the model fidelity related to a conceptual design analysis. Furthermore, methods involving large amplitude responses and large applied inputs have been up to now discarded since the implemented model is linearized around a trim condition and thus may not be reliable for large motion analyses. Anyway, the implemented tool has been developed with a look to future improvements and possibility to host models with higher level of fidelity which could better predict and describe the behavior of a real rotorcraft.

The roll attitude bandwidth testing is based on a frequency domain analysis of the rotorcraft roll response to an applied lateral stick input. This method is also used in the loop for the prediction of Pilot Induced Oscillations (PIO) predisposition [18]. PIO are a typology of Aircraft/Rotorcraft Pilot Coupling (A/RPC), that is adverse, unwanted phenomena originating from anomalous and undesirable couplings between the pilot and rotorcraft. These couplings may result in instabilities which degrade the qualities of flight and sometimes can result in catastrophic accidents.

Comparisons with results from the literature are presented both for validation and for highlighting robustness properties of the control system. Indeed, differences in HQs rating between the actual BO105 and the sized helicopter due to the modeling assumptions (Fig. 8a) mitigate when a flight control system based on a robust approach is activated (Fig. 8b).

Results from HQs assessment are used to modify NDARC input parameters and a re-design process starts with the aim



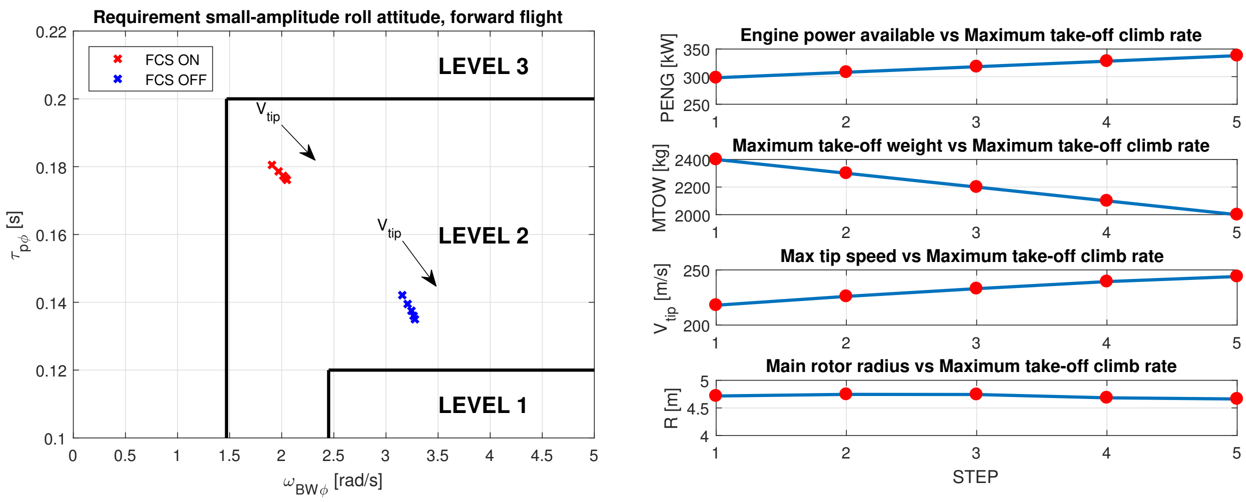
(a) *FCS deactivated* **(b)** *FCS activated*

Figure 8: *Bandwidth and Phase Delay Comparison with Ref. [19].*

of improving HQs levels and ratings.

The methodology implemented in the present tool is inspired by [20]. The objective is to move the position of the points on the bandwidth and phase delay plot in the desired direction in order to reach or get close to a certain HQs level. The main NDARC input parameter employed in order to accomplish this results is the tip speed value. Tip speed cannot be modified as desired, though. Indeed, the requirements and the description of the BO105 in NDARC sizing task leave no margin to increase the parameter without a relaxation of other imposed sizing quantities. Tip speed can be increased for example by increasing engine power available or by reducing maximum take-off weight.

Modifications of these input parameters in the NDARC sizing task affect of course the other sized quantities and in some cases with different trends. That is the case for example of main rotor radius, which decreases when tip speed and engine power available are increased while instead increases when tip speed is increased and maximum take-off weight is decreased. This aspect is exploited for the implementation of re-design logics with the aim of keeping as constant as possible specific quantities (in this case the main rotor radius). Fig. 9a shows the example of HQs rating improvement through the rotorcraft re-design by increasing the tip speed value. Fig. 9b shows the subsequent variations of main sizing parameters and the limited variation of main rotor radius.



(a) *Bandwidth and phase delay method* **(b)** *Main parameters variation*

Figure 9: *Example of results with closure of the loop.*

This approach can be generalized and may be an important feature for the designer both limiting the variation of a quantity of interest and reducing the number of sizing quantities to monitor during the process.

It is worth mentioning that this procedure has been obtained in order to highlight the effects of the re-design of a rotorcraft on HQs ratings. For this reason, heavy re-design of the initial configuration has been performed, in some cases obtaining as an outcome a rotorcraft with general performances strongly reduced just to slightly improve HQs ratings. From an industrial and less theoretical point of view, these results are of course unacceptable. Anyway, useful information and interesting trends for rotorcraft design at the conceptual level of fidelity can be caught from this approach.

VI. Conclusions

In this work the objective of introducing the assessment of HQs during the helicopter conceptual design phase has been pursued. A description has been given about a process to generate and analyze the HQs of rotorcraft derived from the output of the NDARC conceptual design tool.

NDARC software has been deeply used in this work and the output data of the conceptual design tool have provided sufficient information to define a basic rotorcraft flight dynamics model.

Even if many simplifying assumptions have been taken into consideration during the analysis, satisfactory results have been obtained keeping in mind the level of fidelity of the present work. Some modeling problems have arisen during the creation of the flight dynamics model and hints and suggestions have been proposed in order to overcome them. An example is the lack of rotorcraft description in terms of moments of inertia. The flight dynamics module up to now is able to describe single main rotor and tail rotor helicopters but future developments will include models for unconventional rotorcraft configurations in order to make the analysis more general and to investigate the effects of introducing innovative characteristics and components.

For the sake of completeness and generality, the flight dynamics model has been augmented with a flight control system. This aspect has been taken into consideration for a more realistic picture of nowadays rotorcraft, which are in general provided with an augmentation system. Furthermore, this analysis has introduced in the model the dynamics of actuators and sensors, which have contributed in making the rotorcraft description more complete.

An example of HQs and PIO evaluation has been described and applied with the intention to focus the attention on methods compliant with the model fidelity related to a conceptual design analysis. Future developments will include more sophisticated criteria for the assessment of HQs.

At the end, hints and examples have been provided in order to suggest how the conceptual design tool can be included in a loop able to influence the re-design of the rotorcraft.

The implemented tools have all been developed with a look to future improvements and possibility to host higher level models which could better predict and describe the behavior of a real rotorcraft. One example is the automatic generation of output with the aim of coupling the conceptual design tool with the flight simulation facility currently under development at Politecnico di Milano. This will give an important contribution not only in the assessment of HQs and validation of implemented HQs tests but even in the verification of flight dynamics model accuracy and control system calibration.

In general, this work has demonstrated that the description of a rotorcraft, even if with low fidelity models at a conceptual design level, requires to take into consideration technical issues relating to flight dynamics, stability, control and HQs testing, creating a complex environment. Anyway, this approach allowed to analyze the problem of introducing the study of HQs in the rotorcraft conceptual design from a general point of view by facing the problem in its completeness, giving a wide perspective of subjects and issues which an engineer should account for during the design process of a rotorcraft.

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