Augmented Rotorcraft Conceptual Design Driven by Handling Qualities Requirements

Giacomo Gerosa, Andrea Zanoni, Simone Panza, Pierangelo Masarati, and Marco Lovera

Abstract This work presents a rotorcraft conceptual design tool that makes an early account of handling qualities. The conventional sizing is delegated to NDARC, a conceptual design software developed by NASA. The results are used to build a simple flight mechanics model, which is augmented by a simplified flight control system, designed using a structured H_∞ method, with the main aim of determining the requirements in terms of augmentation, rather than of actually designing a flight control system. The handling qualities of the resulting rotorcraft are evaluated objectively, using bandwidth and phase delay requirements from ADS-33. Provisions are also made to support the automatic generation of a flight dynamics model for piloted flight simulation, for the subjective evaluation of handling qualities. The rotorcraft redesign is iteratively performed, based on handling qualities evaluation, until the desired requirements are met. The methodology is applied to the re-desing of a conventional, lightweight helicopter, to illustrate its capabilities.

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1 Introduction

Handling Qualities (HQ) are fundamental in rotorcraft. They determine how safe an aircraft is to fly, and how easily assigned missions can be accomplished by pilots while sparing enough capacity to fulfill other tasks. They are often challenging to assess, particularly for military requirements; significant effort may be required during the development process to make HQs acceptable [1].

Anticipating as much as possible the evaluation of HQs by taking them into account since the very beginning of the design could help reducing the number of modifications that need to be carried out to correct unforeseen unacceptable behavior, as such corrections are the more time and money consuming the later they surface in the design process. However, HQ cannot be easily linked to typical design variables, especially at the conceptual design level, as they depend on parameters which are not usually considered at that stage. Educated guesses are needed, as well as non-trivial engineering judgment, which may result in significant uncertainty on key parameters and performances.

While such an attempt might have been difficult to achieve in the past, today's computational power and well-defined HQ standards offer the possibility, to some extent, to include HQs investigation in multidisciplinary analysis during the conceptual and preliminary design stages.

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 (FCS). Typically, they limit their consideration for FCS to the need to make accommodations for the mass of the required avionics. Indeed, the lack of detailed modeling that is inherent in early stages of design could lead to overlooking a potentially significant contribution to size, weight and performance estimates for some design activities.

Several aerospace research organizations have proposed approaches for multidisciplinary design processes in the field of rotorcraft engineering. Worth of mention are the works of Technion [2], NLR [3], Georgia Tech [4], ONERA [5], DLR [6], and NASA [7].

A rotorcraft conceptual design tool able to include the study of HQs is proposed here, which takes advantage of lessons learned from the previously mentioned works. Figure 1 shows its general architecture.

The process consists of the following steps:

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

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

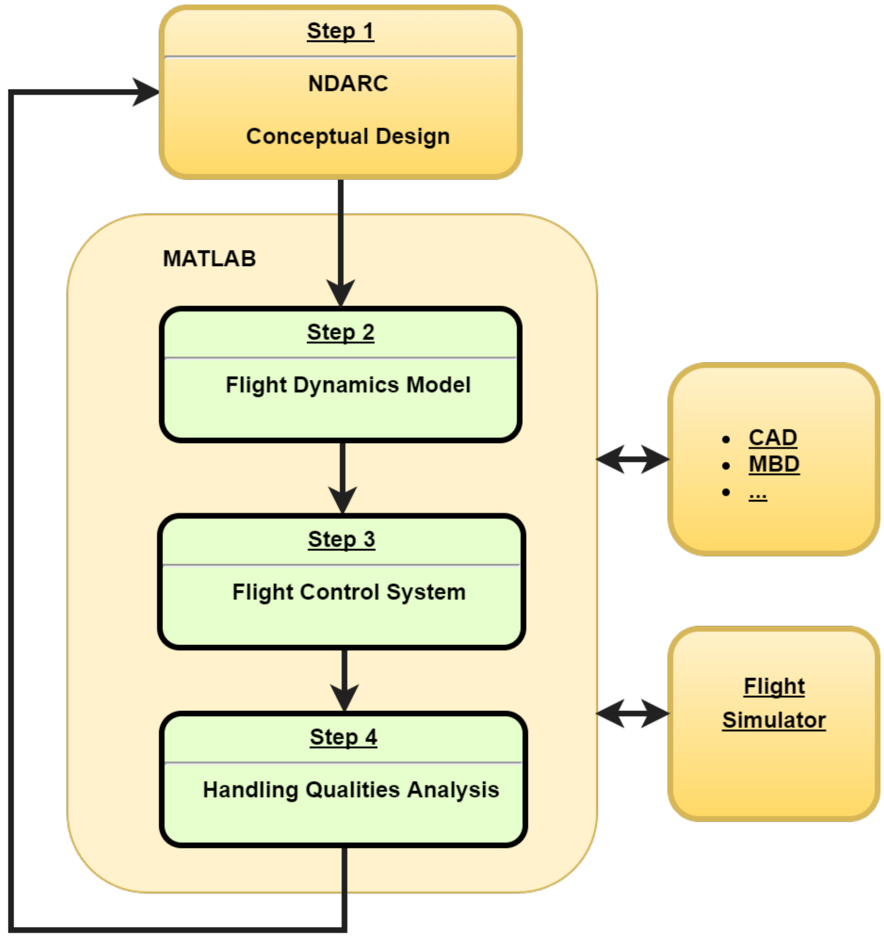


Fig. 1: Rotorcraft conceptual design tool architecture.

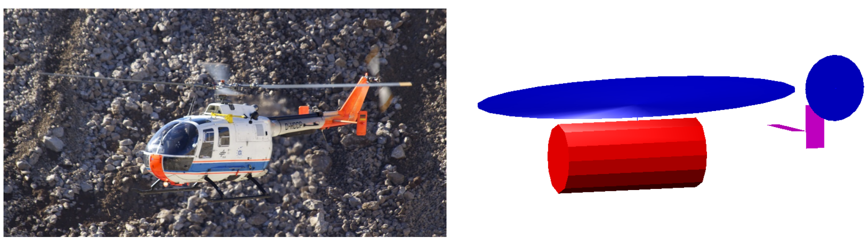
The entire methodology has been developed in Matlab, which provides a suite of toolboxes in support of the required algorithms and models. The tool architecture is general enough to allow hosting data from other analyses (e.g. CAD, Multibody System Dynamics, etc.) and communicate with external software. This feature is important to support the acquisition of additional information, which can be essential in the description of the rotorcraft, and to enable the tool to exchange and compare data from different sources.

A clear example is the automatic generation of a generic rotorcraft model, based on general-purpose multibody dynamics, which is intended for flight dynamics simulation in a piloted flight simulator. This feature may be extremely important in the early verification of flight dynamics and control systems, as it could provide the designer with subjective pilot's contributions in HQs definition and assessment.

2 Conceptual Design with NDARC

For rotorcraft conceptual design step NDARC, an existing, state of the art tool has been selected [8]. NDARC stands for NASA software for Design and Analysis of Rotor-Craft. It performs sizing and analysis tasks starting from an input file that contains the description of the rotorcraft in terms of its constituting components and desired missions and flight conditions. Both tasks are fundamental in the process, as they are needed to compare different architectures and obtain fast results that comply with the desired requirements.

In the present work, input parameters and reference flight conditions for the initial sizing task refer to a light helicopter of the class of the Bölkow (now Airbus Helicopters) BO105 helicopter (Fig. 2a). This reference helicopter has been chosen because of the relevant amount of data available from the open literature. The selected values are reported in Table 1. The rotorcraft resulting from the sizing is a helicopter very similar to the BO105, which it can be compared to. A sketch of the helicopter resulting from NDARC's conceptual design is shown in Fig. 2b.



DLR research helicopter BO105 S123 — Sketch of NDARC's result.

Fig. 3: Comparison between the actual BO105 and the helicopter resulting from NDARC's conceptual design.

The selected sizing approach considers fixed engine power available and maximum take-off weight; design gross weight, empty weight and main rotor radius are sized accordingly, starting from initial guess values.

The main parameters of the BO105 are compared in Table 2 with those resulting from the sizing process.

Once the sizing task is complete, the results are imported in Matlab for further elaboration. NDARC's output file is parsed to extract the input, output and trim parameters required to build the flight dynamics model. Parameters that are not required in the input or generated by NDARC are estimated using analytical or empirical formulas.

Table 1: BO105 sizing missions and flight conditions [9].

Requirement	Value (SI)	Value (english)
Max Endurance	210 min	210 min
Max Range	574 km	310 nm
Max Speed	268 km/h	145 kt
Max Altitude	5180 m	17000 ft
Max Climb Rate	8 m/s	1575 ft/min
Max Climb Rate OEI	0.5 m/s	984 ft/min
Max Take-off Weight	2400 kg	5290 lb
Hover Altitude OGE	1584 m	5200 ft
Hover Altitude IGE	2286 m	7500 ft
Hover Altitude OEI	823 m	2700 ft

Table 2: Results from NDARC initial sizing task.

Variable	Actual BO105		Sized BO105		Diff. [%]
Aircraft					
Weight Empty	1256.0 kg	(2769.0 lb)	1392.9 kg	(3070.8 lb)	+10.9
Design Gross Weight	2200.0 kg	(4850.2 lb)	2024.7 kg	(4463.7 lb)	-7.9
Fuel Tank	400.0 kg	(881.8 lb)	342.1 kg	(754.2 lb)	-14.5
Cruise Drag	1.11 m^2	(11.9 ft^2)	1.12 m^2	(12 ft^2)	+0.1
Main Rotor					
Radius	4.912 m	(16.11 ft)	4.671 m	(15.32 ft)	-4.9
Disk Loading	30.37 kg/m^2	(6.22 lb/ft^2)	29.53 kg/m^2	(6.05 lb/ft^2)	-2.8
Design Blade Loading	0.0660		0.0711		+7.7
Lock Number	5.09		4.26		-16.3
Tail Rotor					
Disk Loading	54.49 kg/m^2	(11.16 lb/ft^2)	56.34 kg/m^2	(11.54 lb/ft^2)	+3.4
Design Blade Loading	0.0742		0.0770		+3.8

The main parameters that describe the rotorcraft at the conceptual design level of fidelity are also exported in a textual file that is used to generate a rotorcraft multibody model for the flight simulation facility currently under development at Politecnico di Milano. Flight dynamics simulation is based on a general-purpose multibody solver, MBDyn [10]; FlightGear is used for visualization [11].

3 Flight Dynamics Model

Data imported in Matlab from NDARC are used to build the flight dynamics model. The model considered in the present work is a conventional, single main rotor and tail rotor helicopter, described using a “hybrid” formulation [12]. The implemented hybrid formulation consists of a 8-DOF flight dynamics model described by a 10-state linear state-space representation:

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

This approach has been selected because with a relatively simple formulation it represents the fuselage-rotor couplings that a 6-DOF model alone cannot capture. Indeed, modeling rotor dynamics has been shown to have a relevant effect on the control law design procedure [13–15]. At the same time, this formulation supports the modeling of rotors by only considering two states for each rotor, avoiding unnecessary complexity in the flight dynamics model.

The linear state-space representation of the model, in the form

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} \tag{1}$$

with

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

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

is obtained by linearizing the nonlinear set of equations that describe the motion of the helicopter about a prescribed trim condition [16].

Trim values are among the variables imported in Matlab from NDARC, which solves the rotorcraft trim problem for controls and aircraft attitude that result in force and moment equilibrium in correspondence to each flight condition and mission segment. For this reason, there is no strict need to perform trim iterations inside the conceptual design tool, accepting the unavoidable minimal discrepancies between the model used in NDARC and the present one, avoiding additional computational cost and guaranteeing sufficient consistency between the NDARC analysis and the flight dynamics model.

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 surfaces, and fuselage [17].

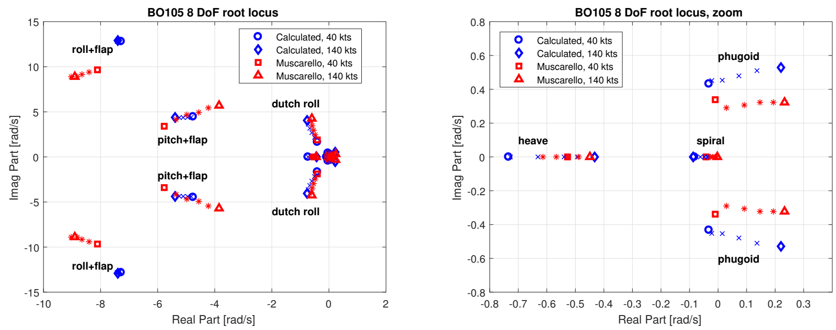
A set of assumptions is introduced to reduce the total complexity and the computational time. Such assumptions produce relatively small errors that are deemed acceptable for helicopter conceptual design. In particular, rotor blades are considered rigid, linearly twisted and untapered. Empirical corrections related to tip loss and root cutout are taken into consideration. The induced velocity is uniform over the disk; tip vortex, stall and compressibility effects are neglected.

An aspect which is worth a specific mention is the estimation of the overall moments of inertia. NDARC does not provide any output regarding mass distribution, since it contains no information, nor makes any assumption, on geometry and mass distribution of the vehicle it sizes. For this reason, moments of inertia have to be calculated during the preliminary computations for stability and control derivatives. Estimation is performed by considering a uniform mass distribution based on mass, position and tentative 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. The foreseen future implementation of external software for CAD or tools for geometry generation may ease the prediction of mass distribution and the calculation of moments of inertia.

The flight dynamics model has been validated through time response analyses and poles position. Figure 5 shows an example of root locus analysis employed for the validation process. The magnitude of the real and imaginary part of the poles, as well as their trend with advance ratio μ variation, is generally captured by the model, compared with those presented in [18], which were obtained with a completely different model, based on a comprehensive rotorcraft aeromechanics tool. Considering the fidelity level of the sizing data and the simplifications made in the present work, and taking into account that reference eigenvalues in [18] have been evaluated thanks to an aeroelastic helicopter model which is definitely more sophisticated than the one implemented in the proposed tool, the results are considered satisfactory for the present analysis.

4 Control System Model

The bare airframe model resulting from NDARC's sizing and its fitting into the flight dynamics model is augmented with a FCS, 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, at



Root locus Root locus zoom

Fig. 5: Root locus comparison between BO105 8-DOF model and [18].

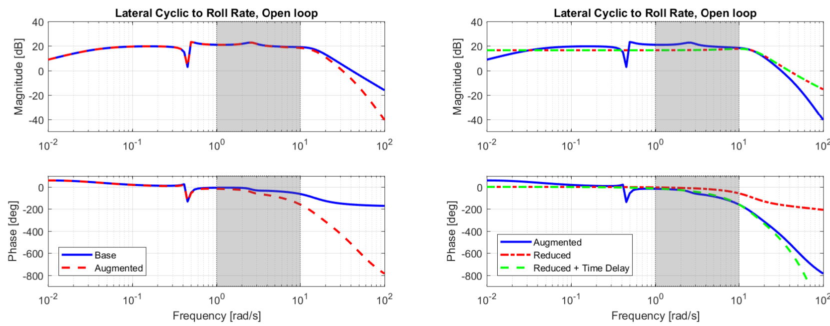
least in the low-speed portion of the flight envelope, and dynamic response for some architectures is strongly dominated by inter-axes cross-couplings [16].

In the implemented flight dynamics model, inputs are directly specified at the swashplate. However, in actual rotorcraft the control inputs are determined by the regulator and actuated through a swashplate, so actuators need to be modeled as well. Similarly, the regulator requires that the states are measured or estimated, thus sensors need to be modeled as well.

Another important aspect is that modern control systems are implemented on digital computers, thus time delays caused by signal transport, processing and filtering have to be taken into account. For simplicity, all these delays are coalesced in an equivalent pure time delay. Both actuators and sensors exhibit their own dynamics; 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. 6a).

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 [19], the bare airframe model is split in two 2nd order single-axis decoupled models that are representative respectively of rotorcraft longitudinal and lateral dynamics in the frequency range 1 rad/s to 10 rad/s. Subsequently, an equivalent pure time delay is introduced in the reduced models, to match the phase delay of the augmented model (Fig. 6b).

At the conceptual design level, the control law should provide the rotorcraft with stabilization and with a basic level of augmentation, as needed for HQs assessment. The structure of the control law should be kept as simple as possible (e.g. static feedback gains and PID controllers), compatibly with the overall fidelity level of the analysis in the early design stage, and keeping in mind practical implementability as a primary goal. It is of utmost importance to take into account that the model description is uncertain by definition, as it refers to an aircraft that does not exist, yet. For this reason, the control design procedure needs to account for characteristics of the model that are not modeled or may vary widely. Furthermore, many



Augmented model Reduced model

Fig. 7: Bode Plot for flight dynamics reduced models on roll axis.

requirements in terms of rotorcraft response capabilities and standards have to be taken into account during the synthesis of the regulator. In essence, the sizing of the control law, in accordance with the spirit of a conceptual design, should be intended as an estimation of the amount of control effort that will be required by the design, rather than as the actual sizing of a full-featured control strategy.

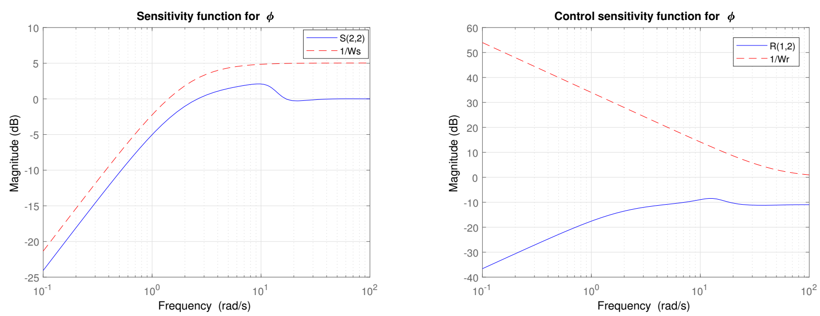
Based on the above considerations, the H_∞ framework has been chosen to carry out the design of the control laws [20]. The H_∞ approach is a modern control technique suitable for MIMO systems and for dealing with model uncertainty and multiple requirements. In particular, a structured H_∞ method is implemented, in order to impose *a priori* the structure of the control law architecture, 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. A systematic approach to apply the structured H_∞ framework to control law design of rotorcraft in several configurations was presented in [21].

The following requirements were considered in the analysis.

- Performance requirements are addressed by imposing weights on the sensitivity function, which can be interpreted as the closed-loop transfer function from pilot reference input to tracking error (thus related to command tracking performance) or from disturbance on the output variable to the output itself (thus related to disturbance rejection performance). 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. 8a). In [22], disturbance rejection bandwidth (DRB) and peak (DRP) have been proposed as metrics to assess performance related to disturbance rejection, along with related boundaries; it is straightforward to encode these requirements in the form of a weighting function on sensitivity.
- Control action moderation requirements are addressed by imposing weights on the control sensitivity function. Indeed, control action is provided by actuators,

which have limited control authority both in stroke and rate, and limited bandwidth. The control sensitivity function can be interpreted as the transfer function from reference signal to control action, or equivalently as the transfer function from disturbance on the output to control action, or 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 beyond the bandwidth of the system (Fig. 8b);

- Robustness with respect to uncertainty is addressed by imposing a frequency representation of model uncertainty as a weight on the complementary sensitivity function. The weight on the complementary sensitivity function can be chosen based on a multiplicative uncertainty description: that is, the magnitude of the weighting function represents the amount of relative uncertainty of the perturbed model with respect to the nominal one as a function of frequency in the worst-case.



Sensitivity function   Control sensitivity function

Fig. 9: Sensitivity and control sensitivity functions from regulator synthesis.

Robustness requirements need particular mention, since quantities resulting from conceptual design show a high degree of uncertainty, owing to the fact that the physical parameters values (e.g. mass and inertia) obtained as the result of preliminary sizing will unavoidably differ from the final design values. Robustness to this uncertainty is needed to guarantee the stability of the closed-loop system during the optimization process [23].

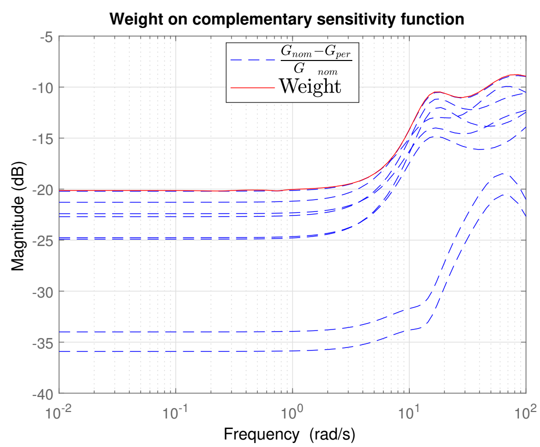
Figure 10a shows an example of weight choice for robustness requirements in case of uncertain moment of inertia values. Indeed, moments of inertia are not computed by NDARC and, without a CAD model as in the present case, an estimate of their values is necessary to obtain the flight dynamics model. Uncertainty on their values is thus taken into account in the present analysis by considering a nominal model (i.e. obtained by imposing nominal pitch and roll inertia values) and a set of perturbed models, obtained by applying up to $\pm 10\%$ uncertainty on roll and pitch moments of inertia. The uncertainty frequency weighting function is obtained by considering the upper-bound of the relative errors between the frequency response of the nominal and the perturbed model, frequency-by-frequency. Let $G_{nom}(s)$ be the transfer function of the nominal model and $G^{i}_{per}(s)$ be the transfer function of the i-th perturbed model in the set; the relative error between the i-th model and the nominal one is defined as

$$e_i(\omega) = \frac{G^{i}_{per}(j\omega) - G_{nom}(j\omega)}{G_{nom}(j\omega)} \tag{2}$$

and the upper-bound is obtained as

$$l(\omega) = \max_{i} |e_i(\omega)| \tag{3}$$

The uncertainty frequency transfer function is obtained by fitting the upper-bound with a rational, proper transfer function which is then employed in the control design procedure.



Complementary sensitivity function weight

Fig. 11: Weights on sensitivity functions for regulator synthesis.

A thorough analysis of possible sources of uncertainty in the model, and the formulation of the corresponding perturbed models, transfer functions $G^{i}_{per}(s)$, and errors $e_i(\omega)$, is beyond the scope of this work. In fact, as discussed earlier, in such an early conceptual design stage, we are mainly focusing on defining requirements in terms of required authority and augmentation that needs to be provided by the AFCS, rather than with its detailed design and verification. Nonetheless, its investigation represents a rather interesting possible development of the present work.

5 Handling Qualities Assessment

The final step of the loop consists in a HQs assessment procedure. HQs analysis is performed by applying the bandwidth and phase delay requirement from the Aeronautical Design Standards, ADS-33E-PRF [24]. ADS-33 supports HQs investigation through a mission-oriented approach based on mission task elements performed with different usable visual cue environments.

The bandwidth and phase delay requirement is implemented for the analysis of small-amplitude roll attitude changes in forward flight. It 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 on a criterion that is compatible with the model fidelity related to conceptual design analysis. Furthermore, methods involving large amplitude responses and large applied inputs have been up to now discarded since the model used in the analysis 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 at future improvements and the possibility to host models with higher level of fidelity, which could better predict and describe the behavior of a real rotorcraft.

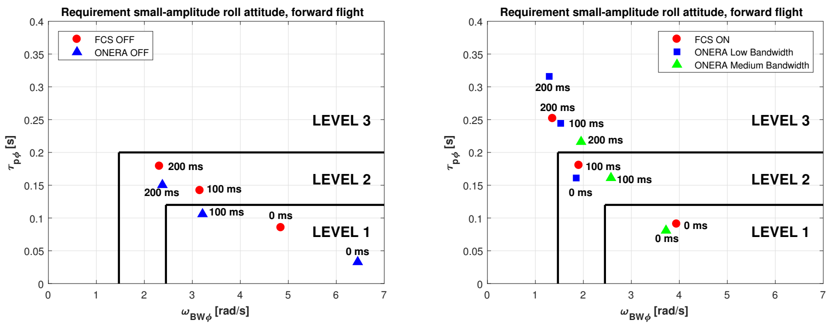
The roll attitude bandwidth testing is based on a frequency domain analysis of the rotorcraft roll response to an applied lateral stick input. This method is also used in the loop for the prediction of Pilot Induced Oscillations (PIO) proneness [25]. PIOs are a type of Aircraft/Rotorcraft Pilot Coupling (A/RPC), namely adverse, unwanted phenomena originating from anomalous and undesirable interaction between the pilot and rotorcraft dynamics. These couplings may result in instabilities which degrade the quality of flight and sometimes can result in catastrophic loss of control.

A comparison with results from the literature is 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. 12a) significantly reduce when a FCS based on a robust approach is activated (Fig. 12b).

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

The methodology implemented in the present tool is inspired by [27]. 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 at least get close to a certain HQs level. The main NDARC input parameter employed to accomplish this result is the main rotor tip speed value. The tip speed cannot be modified as desired, though. Indeed, the requirements and the description of the vehicle in the NDARC sizing task leave no margin to increase that 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.

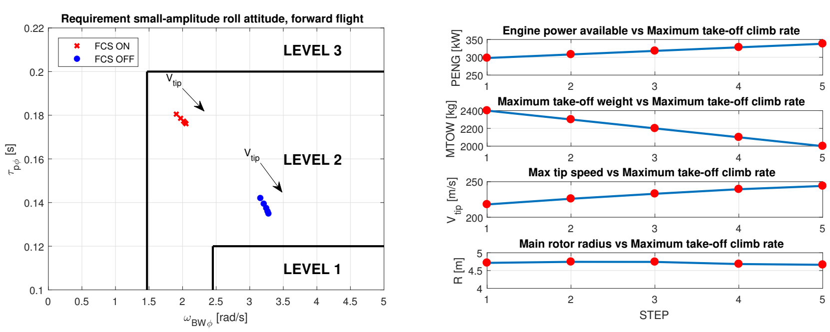
Modifications of these input parameters in the NDARC sizing task affect of course the other sized quantities and in some cases with different trends. This is the case for example of the main rotor radius, which decreases when tip speed and



FCS deactivated FCS activated

Fig. 13: Bandwidth and Phase Delay Comparison with [26].

engine power available are increased, whereas it increases instead when tip speed is increased and maximum take-off weight is decreased. This aspect is exploited for the implementation of re-design logic with the aim of keeping specific quantities as constant as possible (in this case, the main rotor radius). Figure 14a shows the example of HQs rating improvement through the rotorcraft re-design by increasing the tip speed value. Figure 14b shows the subsequent variations of the main sizing parameters and the limited variation of main rotor radius.



Bandwidth and phase delay method Main parameters variation

Fig. 15: 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 captured by this approach.

6 Conclusions

This work pursued the objective of introducing the assessment of HQs during the helicopter conceptual design phase. The described process generates and analyzes the HQs of rotorcraft derived from the output of NDARC, a rotorcraft conceptual design tool developed by NASA. Its output has been used to define a basic rotorcraft flight dynamics model. Even if many simplifying assumptions have been made during the analysis, satisfactory results have been obtained, taking into account the low level of fidelity addressed by the present work. Modeling problems arising during the creation of the flight dynamics model and caused by an inherent lack of detailed information have been overcome using sound estimations. An example is the lack of rotorcraft description in terms of moments of inertia. The current flight dynamics module is able to describe single main rotor and tail rotor helicopters; future development will address unconventional rotorcraft configurations, to make the analysis more general and to investigate the effects of introducing innovative characteristics and components. The flight dynamics model has been augmented with a flight control system. In fact, modern rotorcraft always feature at least some form of stability and control augmentation systems. The dynamics of actuators and sensors have been also considered, to make the rotorcraft description more complete. An example of HQs and PIO proneness evaluation has been described and applied, based on bandwith and phase delay requirements from ADS-33, to focus on methods compliant with the model fidelity related to conceptual design analysis. Future development will consider more sophisticated criteria for the assessment of HQs. The proposed tools have all been developed with a look at future improvements and the possibility to use higher fidelity models, which could better predict and describe the behavior of a real rotorcraft. One example is the automatic generation of a generic nonlinear helicopter model based on multibody dynamics, to couple the conceptual design tool with the flight simulation facility currently under development at Politecnico di Milano, to support subjective assessment of HQs and validation of implemented HQs tests, and eventually also the verification of flight dynamics model accuracy and control system calibration. As a general remark, this work showed that the description of a rotorcraft, even if with low fidelity models at a conceptual design level, requires one to account for technical issues related to flight dynamics, stability, control and HQs testing, creating a complex environment. This approach supported the introduction of HQs assessment in 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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References

1. Gareth D. Padfield. Rotorcraft handling qualities engineering: Managing the tension between safety and performance. *Journal of the American Helicopter Society*, 58(1):1–27, 2013. doi:10.4050/JAHS.58.01.1001.
2. Omri Rand and Vladimir Khromov. Helicopter sizing by statistics. 49(3):300–317, 2004. doi:10.4050/JAHS.49.300.
3. Jan-Floris Boer and Jos Stevens. Helicopter life cycle cost reduction through pre-design optimisation. 2006.
4. Adeel Khalid and Daniel P. Schrage. Helicopter design cost minimization using multidisciplinary design optimization. In *AHS 63rd Annual Forum*, Virginia Beach, VA, May 1–3 2007.
5. PM Basset, A Tremolet, F Cuzieux, C Schulte, D Tristrant, T Lefebvre, G Reboul, M Costes, F Richez, S Burguburu, et al. The creation project for rotorcraft concepts evaluation: The first steps. 2011.
6. Alex Krenik and Peter Weiand. *Aspects on Conceptual and Preliminary Helicopter Design*. Deutsche Gesellschaft für Luft-und Raumfahrt-Lilienthal-Oberth eV, 2016.
7. Ben Lawrence, Colin R Theodore, and Tom Berger. Handling qualities optimization for rotorcraft conceptual design. 2016.
8. Wayne Johnson. Ndarc-nasa design and analysis of rotorcraft theoretical basis and architecture. 2010.
9. Edwin D McConkey, Robert K Anoll, Margaret B Renton, and James Young. Helicopter physical and performance data. Technical report, Systems Control Technology, inc., Arlington, VA, 1991.
10. Pierangelo Masarati, Marco Morandini, and Paolo Mantegazza. An efficient formulation for general-purpose multibody/multiphysics analysis. 9(4):041001, 2014. doi:10.1115/1.4025628.
11. Andrea Zanoni, Luca Conti, and Pierangelo Masarati. FRAME-Sim: a free-software, multibody-based, pilot in the loop rotorcraft flight simulator. In *ASME IDETC/CIE 2018*, Quebec City, Canada, August 26-29 2018. DETC2018-85289.
12. Mark B Tischler and Robert K Remple. Aircraft and rotorcraft system identification. *AIAA education series*, 2006.
13. M. B. Tischler. System identification requirements for high-bandwidth rotorcraft flight control system design. In *American Control Conference, Boston, USA*, 1991.
14. S. J. Ingle and R. Celi. Effects of higher order dynamics on helicopter flight control law design. *Journal of the American Helicopter Society*, 39(3):12–23, 1994.
15. W. E. Hall Jr. and A. E. Bryson Jr. Inclusion of rotor dynamics in controller design for helicopters. *Journal of Aircraft*, 10(4):200–206, 1973.
16. Gareth D. Padfield. *Helicopter Flight Dynamics: The Theory and Application of Flying Qualities and Simulation Modelling*. Blackwell Publishing, 2007.
17. Raymond W Prouty. *Helicopter performance, stability, and control*. 1995.
18. Vincenzo Muscarello, Giuseppe Quaranta, Pierangelo Masarati, Linghai Lu, Michael Jones, and Michael Jump. Prediction and simulator verification of roll/lateral adverse aeroservoelastic rotorcraft–pilot couplings. *Journal of Guidance, Control, and Dynamics*, 2015.
19. S. Panza and M. Lovera. Rotor state feedback in the design of rotorcraft attitude control laws. In *3rd CEAS Specialist Conference on Guidance, Navigation and Control, Toulouse, France*, 2015.

20. Sigurd Skogestad and Ian Postlethwaite. *Multivariable feedback control: analysis and design*, volume 2. Wiley New York, 2007.
21. S. Panza. *Structured flight control law design for helicopters and tiltrotors*. PhD thesis, Politecnico di Milano, Dipartimento di Scienze e Tecnologie Aerospaziali, 2018.
22. T. Berger, C.M. Ivler, M.G. Berrios, M.B. Tischler, and D.G. Miller. Disturbance rejection handling qualities criteria for rotorcraft. In *72nd Annual Forum of the American Helicopter Society, West Palm Beach, USA*, 2016.
23. S. Panza and M. Lovera. Rotor state feedback in helicopter flight control: robustness and fault tolerance. In *IEEE Multi-Conference on Systems and Control, Antibes-Nice, France*, 2014.
24. Aeronautical Design Standard. Handling qualities requirements for military rotorcraft. *ADS-33D, US Army, St. Louis, MO*, 1994.
25. Marilena D Pavel, Michael Jump, Binh Dang-Vu, Pierangelo Masarati, Massimo Gennaretti, Achim Ionita, Larisa Zaichik, Hafid Smaili, Giuseppe Quaranta, Deniz Yilmaz, et al. Adverse rotorcraft pilot couplings–past, present and future challenges. *Progress in Aerospace Sciences*, 62:1–51, 2013.
26. Marilena D Pavel, J Götz, B Vu, and Michael Jump. Adverse rotorcraft-pilot coupling: Prediction and suppression of rigid body RPC: Sketches from the work of GARTEUR HC AG-16. In *34th European Rotorcraft Forum, 1-15, 2008*. Royal Aeronautical Society, 2008.
27. Deniz Yilmaz, Marilena D Pavel, and Ilkay Yavrucuk. Helicopter design for handling qualities enhancement. 2009.