Helicopter flight control design tool integrating handling qualities requirements

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Abstract
As a first step to establish a method to configure helicopter autopilots in order to handle at best the requirements of Handling Qualities described in ADS-33 standards, a tool has been developed to help in the designing work. This paper covers a complete adjustment made using this software for the Attitude Control law, using pole placement, attitude quickness and bandwidth / phase delay criteria, and taking into account static actuators saturations. Then, some interesting insight into specific gain tuning sensitivity properties to standards is obtained, and these can lead to further studies.

1. Introduction

The helicopter is naturally an unstable system. For a rotorcraft without any piloting assistance, the pilot has to maintain a constant effort to overcome this problem and keep it stabilized. Furthermore, he has to manage the trajectory, keeping in mind the imperfections of the handling qualities of the aircraft. Then, some piloting assistance technologies (AP (Auto-Pilots), AFCS (Automatic Flight Control Systems) and FBW/FBL (Fly-By-Wire/Fly-By-Light)) have been progressively implemented on these systems in order to reduce the piloting workload for the benefit of mission and armament management tasks.

The complexity of flight mechanics of rotorcraft and the increasing requirements in handling qualities make the autopilots designing work particularly tricky. The French Aerospace Laboratory (ONERA) has led studies for many years about designing control laws for helicopters, integrating handling qualities requirements from ADS-33 standards [1] since the concept-stage, as it is presented for example in references [8] and [9]. This paper will show the first stages of a Ph.D. thesis-work in progress in this context. Otherwise, only NASA has already led such studies, which have permitted the development of the CONDUIT software [3]. Moreover, classical methods well known by automation engineers can not be directly applied as they do not treat the criteria used by this standard.

The first section will introduce the reader to the classical linear state space model of helicopters used and the control law which had been chosen to be designed. The second section will show the three selected criteria and the associated tool developed to evaluate them, depending on the design. The last section is the explanation of an example design made using the tool.

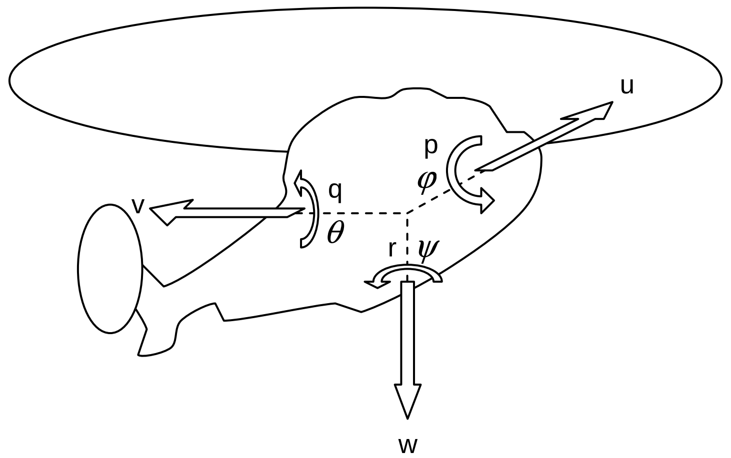
1.1 Linear state space model of a helicopter

We can find in Figure 1 a schema describing the main dynamical variables used to represent the flight dynamics of a helicopter.

Let U, X, Y respectively be the input, state and output vectors of the state space model of a helicopter, such that $U = [DDZ, DDL, DDM, DDN]^t$ and $Y = X = [u, v, w, p, q, r, \varphi, \theta, \psi]^t$ (with “ M^t ” denoting the transpose matrix of “ M ”). The next paragraph will explain how to use the input U to control the helicopter. To help understanding it, the Figure 2 can be useful as it describes the sticks, with a schematic of a cockpit from a pilot point of view.

The collective stick DDZ is connected to the swashplate and permits the control of the rotor lift force magnitude by modifying the average component of the blades pitch angle. The cyclic stick allows changing the 1-per-rev harmonics of the blades pitch angle, and thus controlling the roll and pitch moments of the rotor. This results in the orientation of the rotor around its roll axis (roll rate p and bank angle ϕ) when acting on the lateral cyclic input (DDL), and on the pitch axis (pitch rate q and attitude θ) when acting on the longitudinal cyclic input (DDM). The pedals (DDN) allow the control of the anti-torque (tail) rotor and the motion of the helicopter around its yaw axis (yaw rate r and heading ψ).

We will use the following notations: A is the state matrix, B is the command matrix, C is the observation matrix and D is the input/output coupling matrix.



DDZ	: collective pitch	/1
DDL	: lateral cyclic	/1
DDM	: longitudinal cyclic	/1
DDN	: pedals	/1
u	: longitudinal speed	m/s
v	: lateral speed	m/s
w	: vertical speed	m/s
p	: roll rate	rad/s
q	: pitch rate	rad/s
r	: yaw rate	rad/s
φ	: bank angle	rad
θ	: pitch angle	rad
ψ	: heading angle	rad

Figure 1: Main parameters of a helicopter – inputs and states.

Here, we will consider that $C = I_{9x9}$ and $D = 0_{9x9}$, such that the linear state space model of the helicopter is (using usual linear assumptions around equilibrium status):

$$\Sigma : \begin{cases} \dot{X} = A.X + B.U \\ Y = X \end{cases} \quad \textbf{(1)}$$

For further details on helicopters modelling, one can have a look at [2] and [6]. For the results shown thereafter, we have used a generic model of 10-ton class helicopter.

1.2 The case study of this paper relatively to standards (ADS-33)

The standards specify the Handling Qualities (HQ) of a wide range of helicopters. All criteria depend on the case study, and they are detailed in a specific classification.

First, the helicopters are indexed into 4 rotorcraft categories: attack, scout, utility and cargo. This paper will focus on the study of a 10-ton class helicopter: cargo-type. A table in the standards specify which Mission Task Elements (MTE) the studied helicopter should be able to do, and the required agility needed for each one. Here, limited or moderate agility are needed for all cases. In this paper, we will focus on the specifications described upon with the “limited agility” requirements only.

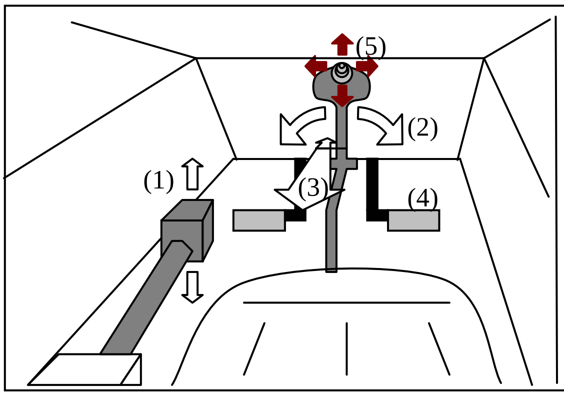
Then, the case studies are divided in two parts: hover and low speed, and forward flight. For this paper the study is only limited to hover and low speed flight conditions, the hover being used as the design point.

Then, a rating of Usable Cue Environment (UCE 1, 2 or 3) is provided. We have decided to study the case of UCE 2, which means the pilot “can make limited corrections with confidence, and precision is only fair”.

Depending on the UCE and the case study of flight chosen (hover or forward flight), a table specifies the required response type. Here, the Attitude Command Attitude Hold (ACAH) response-type is needed to be able to achieve Level 1 response type rating. The next sub-section will make a brief description of the specific ACAH response-type used in this case study.

1.3 The Attitude Command Attitude Hold control law studied (ACAH): Attitude retention (ATT)

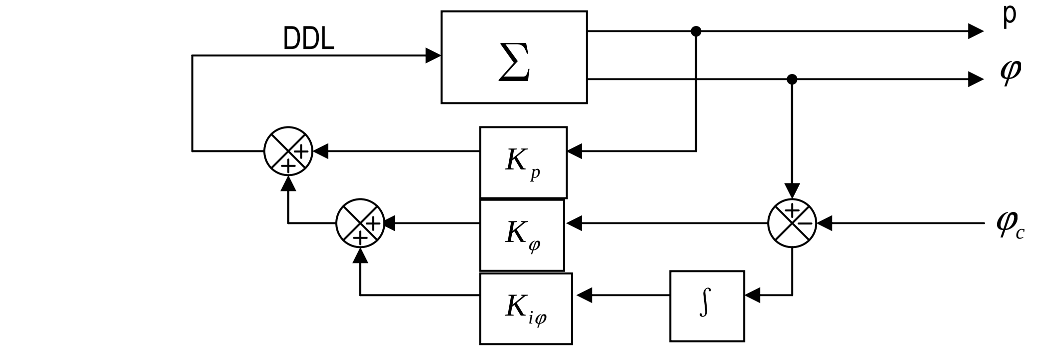
In an Auto-Pilot, the attitude retention control law (ATT) is a control mode which permits to maintain the attitudes of the helicopter (φ, θ), governed by the hat switch of the cyclic stick. The Figure 2 shows the pilot point of view of a cockpit, and shows the hat switch with the available positions in red. We can find in Figure 3 a schema describing the ATT law on the lateral axis only. The associated feedback equations are given in (2).



(1) DDZ : collective pitch /1
(2) DDL : lateral cyclic /1
(3) DDM: longitudinal cyclic /1
(4) DDN: pedals /1

(5) Hat switch (used with ATT)

Figure 2: Main controls available in the cockpit (pilot point of view).



K_p : derivative gain (rate damping) K_φ : proportional gain $K_{i\varphi}$: integral gain φ_c : target bank angle

Figure 3: Attitude retention control law applied on roll axis.

Thus, for the roll axis, the pilot can modify the target bank angle with the lateral control of the hat switch. As for an example, keeping activated the hat switch to the right can increase the value of φ_c by 2deg/sec (depending on the adjustment).

$$\begin{cases} DDL = K_p.p + K_{\varphi}.(\varphi - \varphi_c) + K_{i\varphi}.\int(\varphi - \varphi_c) \\ DDM = K_q.q + K_{\theta}.(\theta - \theta_c) + K_{i\theta}.\int(\theta - \theta_c) \\ DDN = K_r.r + K_{\psi}.(\psi - \psi_c) + K_{i\psi}.\int(\psi - \psi_c) \end{cases} \quad \textbf{(2)}$$

The PhD thesis work aims at elaborating a method to configure the Auto-Pilots in order to handle as much as possible the requirements of ADS-33. In this paper, we will focus on studying the sensitivity of the derivative, proportional and integral gains to some of the criteria of this standard. The next section will make a brief description of the selected criteria.

2. Selected criteria from standards ADS-33 and associated tools developed

A tool has been developed to help the understanding of the gain-tuning sensitivity study. The whole development for the tool has been made under MATLAB® v7. The following sub sections will describe the selected criteria shown on Figure 4 that have been integrated in this tool.

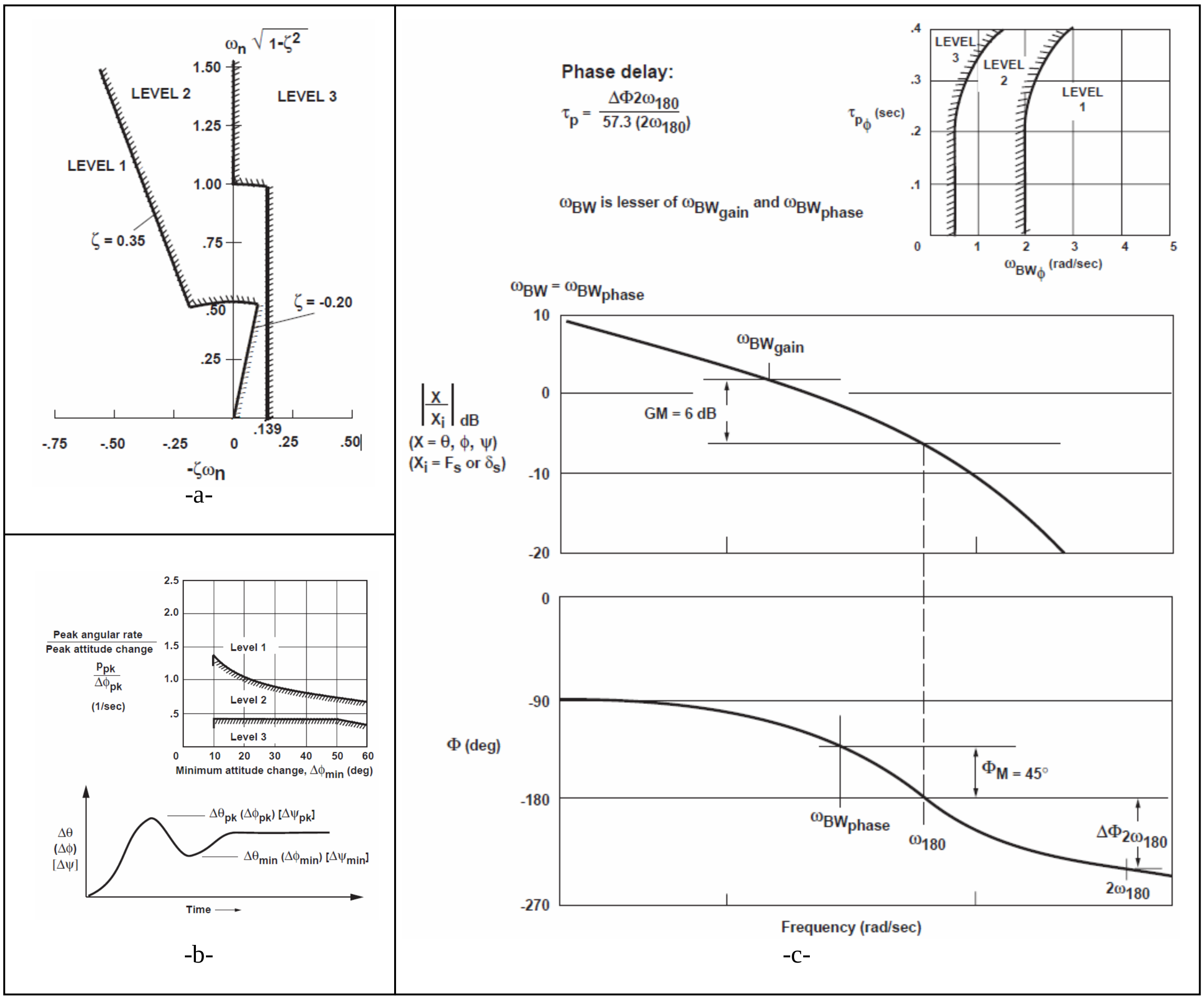


Figure 4: Selected criteria from AD-S33 standards [1]. (a): Eigenvalues. (b): Attitude Quickness. (c): Bandwidth / Phase Delay.

With the term of “Flying Qualities”, we refer to all the necessary qualities a helicopter needs so that an average pilot can easily perform all mission tasks precisely and safely. During the process of designing control systems, we aim to satisfy a good level of Handling Qualities. In that purpose, we use the design guide available in the ADS-33 standards developed by US-Army. These same standards explain how to experimentally evaluate the Handling Qualities in order to verify the good behaviour of the flight control system (FCS).

The three selected criteria for this case study are eigenvalues, attitude quickness, bandwidth/phase delay, and they respectively evaluate the helicopter’s stability, agility and ability to fly with precision: these constitute the basis of the handling qualities of a helicopter. The aim is to place the resulting point obtained for each criterion in the “LEVEL1” area of the associated plots. The limits of the areas depend on: the studied axis, the UCE (Usable Cue Environment), the required agility with the MTE (Mission Task Element), the required response-type, the speed of flight (hover and low speed, or forward flight) and the rotorcraft category. We have already chosen a case study in part 1.2.

2.1 Eigenvalues: stability criterion

This criterion is evaluated by calculating the eigenvalues of the dynamic matrix of the closed loop system, and their positions in Figure 4 (a) determine the quality of the helicopter stability. This specific problem itself is already hard as it is very constrained. We can find in [4] an interesting analytic way to try to solve it. However, the results of the applied method will not be shown here. The idea is not fully abandoned but it does not take into account the whole set of criteria used in this study, and we easily tend to lose sight of the physical aspects of the complete problem following this way.

2.2 Attitude Quickness: agility criterion

For moderate amplitude attitude changes, the agility is evaluated using attitude capture flight tests. For the gains sensitivity study, the same procedure is applied during computations. Attitude change simulations are performed and the criterion is computed using three characteristic parameters: the peak angular rate, the peak attitude change and the minimum attitude change, as defined on Figure 4 (b). The placement of the resulting point will determine the quality of the helicopter agility.

2.3 Bandwidth / Phase Delay: a criterion to evaluate the ability to fly with precision

For small amplitude attitude changes, the helicopter frequency response is used. For the linear models used in this study, the classical Bode plots of the linearized transfer functions between the attitude control inputs and the attitudes of the helicopter are used (see Figure 4 (c)). The placement of the resulting point will determine the ability of the helicopter to fly with precision. The usual way to determine this criterion in flight is to perform frequency sweeps on the studied axis input and to make the associated analysis to generate the frequency plot. The tool developed during this work is also able to simulate this kind of flight tests and to perform the associated spectral analyses.

2.4 Computer Aided Setting and Tuning tool for HELicopters’ AutoPilots v1 (CAST-HEL-AP)

The calculations of the criteria have been integrated in a tool developed on MATLAB®. We can find a screenshot of this tool in Figure 5. We can recognize on the screenshot the plots of the three criteria and the associated simulations and calculations.

The tool is divided into two main parts:
- bottom part: gain tuning area (with save/load functionalities)
- upper part : helicopter model selection and analysis, divided itself in 4 columns
    - 1st column: we can find the plot of eigenvalues, as well as the case study chosen (thanks to which the tool will adapt the specific limits)
    - 2nd to 4th columns: each column ties with an axis analysis (roll, pitch and yaw). The upper part helps making the attitude quickness analysis, and we can see 3 plots showing respectively the actuators needs, the control input with the associated response of the system, and the resulting calculated point on the criteria plot. The bottom part helps making the bandwidth/phase delay analysis, and we can see 3 plots showing respectively Bode gain, phase gain and the resulting calculated point on the criteria plot.

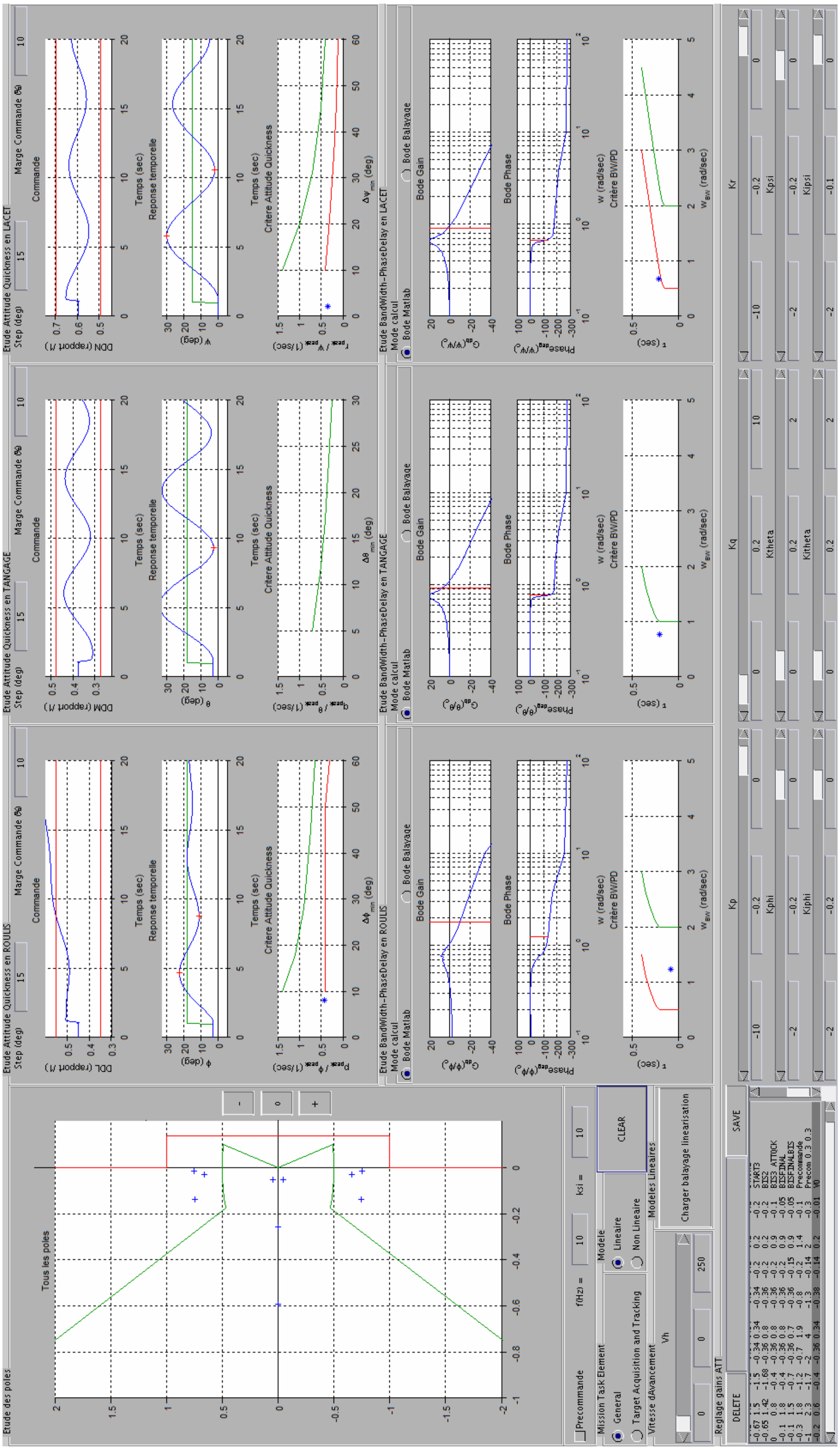


Figure 5: CAST-HEL-AP (Computer Aided Setting and Tuning tool for HELicopters' AutoPilots v1).

The tool is designed in such a way that it automatically generates all necessary simulations for ADS-33 criteria computations. Visualisation of the results easily highlights the controllers' saturations, due to the physical constraints on serial actuators. A complete calculation for a specific linear configuration needs around up to 0.5 seconds (under MATLAB® v7 R14 SP3, processor: Opteron model 8389, 2.9 GHz, 512 Ko, 128 Go). This short computational time combined with the simultaneous study of the 3 criteria sensitivities to the FCS gains, considerably improves the efficiency of the gain tuning process.

The purpose of the next section is to show the interest of this kind of tool with a specific case study. Then, a summary of the lessons learned from the usage of this tool is given, and some interpretations are done.

3. Designing an ATT control law of a 10-ton class helicopter in linear assumptions using CAST-HEL-AP

The design study presented here has been made using all previous assumptions, adding delays and actuators linear models on each command axis. Here is summarized the list of assumptions considered:

- 10-ton class helicopter. Category: cargo. Required agility: limited agility. MTE: All others MTE (general on the software).
- Hover and low speed (Vh = 0 km/h).
- UCE: 2, NoE (Near of Earth). Response-type studied: ACAH (Attitude Command, Attitude Hold).
- LVL1 achievable angle: 15°.
- Limits on commands: +/-10% of maximum range available on *U*.
- Delay values: 0.1 sec.

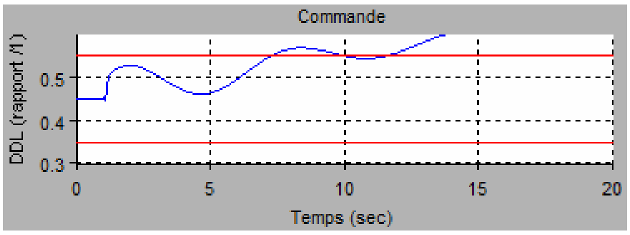
Tunings have been done using the tool developed during this work. This permitted to obtain some interesting insight into the gain tuning sensitivity upon the criteria, and to find an interesting configuration which handle as much as possible the Handling Qualities specified on the standards. In some cases, aiming to achieve high HQ numbers (criteria values) for this class of helicopter leads to a lack of solution, which means no configuration could permit to get to the LEVEL1 area for all criteria. In some hard cases, it came out that even stabilization was not possible with the performance targeted. Thus, the first designs showed that the criteria values were sometimes too high. The following designs, with softer constraints, were more successful and this could teach us some interesting properties, which are summarized in next sub-sections.

3.1 Strategy used during the complete design

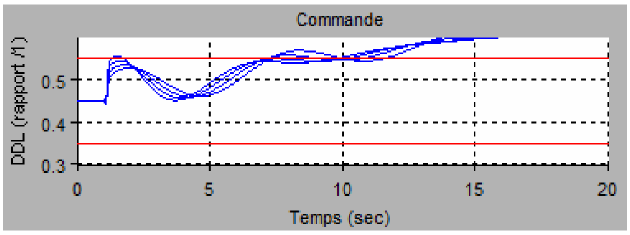
For each design, we have followed the steps described thereafter. We have chosen to develop the details for the roll axis only, but the complete work has been made on each axis, and the final result is shown at the end.

3.1.1 Saturation of actuators and proportional gains

First, the proportional gains are modified in order to use the whole capability of the actuators (during the first seconds, with the peak). Figure 6 shows the adjustment made for this gain following this strategy.



(a)



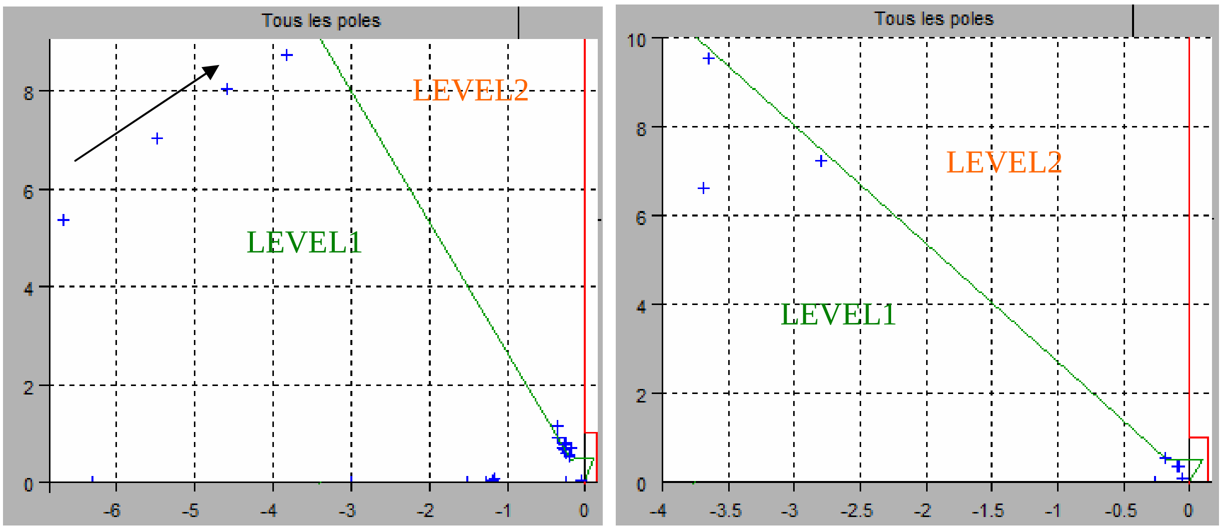
(b)

Figure 6: Tuning on K_φ from -0.2 (a) to 0.35 by 0.05 steps (b).

The same work is done on each axis. Thus, thanks to these modifications, the qualities of the stability and agility of the helicopter are really well upgraded.

3.1.2 Improving the stability with the derivative gains

Then, the derivative gains were tuned in order to place the eigenvalues at LEVEL1/LEVEL2 boundary for the pole placement criteria (for fast modes). The aim was to increase these gains to the maximum possible in order to stabilize the system as much as possible for slow modes. The plot showing eigenvalues of the system is useful there, and we can see the impact of this modification in Figure 7 (a). Figure 7(b) shows the eigenvalues once the derivative gains have been modified on all axes (Figure 7 (b)).

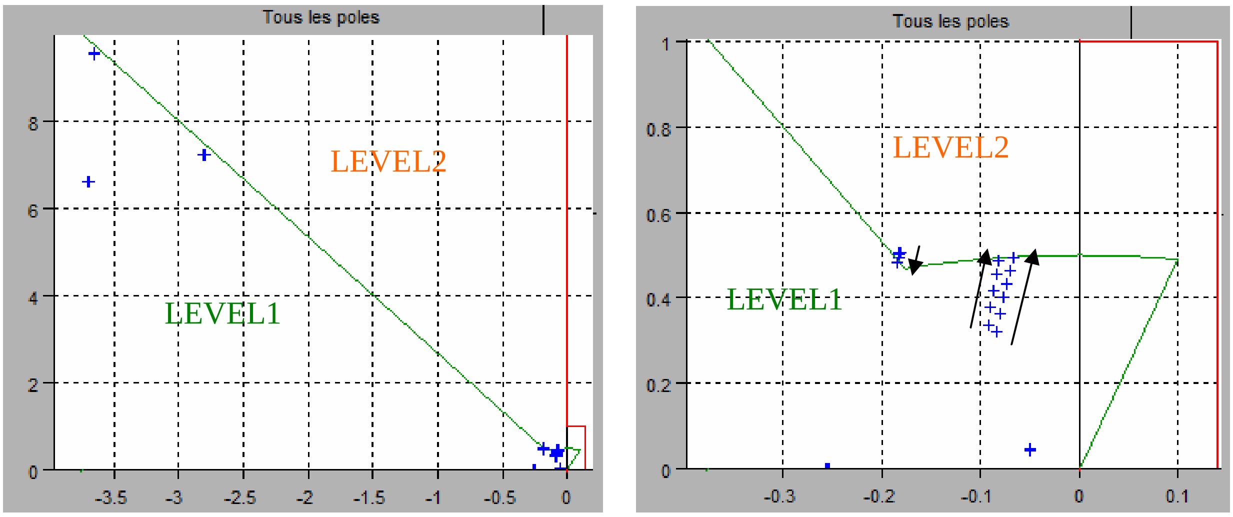


(a) (b)

Figure 7: (a) Tuning on K_p from -0.3 to -0.6 by -0.1 steps. (b) A configuration with all derivative gains modified (on all axes).

3.1.3 Reducing steady-state error with integral gains

The next step consists in modifying the integral gains in order to reduce the steady-state error, keeping in mind to stay in the LEVEL1 stability area for the pole placement criteria: we place (as much as possible) all the eigenvalues near the LEVEL1/LEVEL2 limit for the pole placement criterion. Here $K_{i\varphi}$ has been reduced from -2.0 to -1.8 (by +0.1 steps).



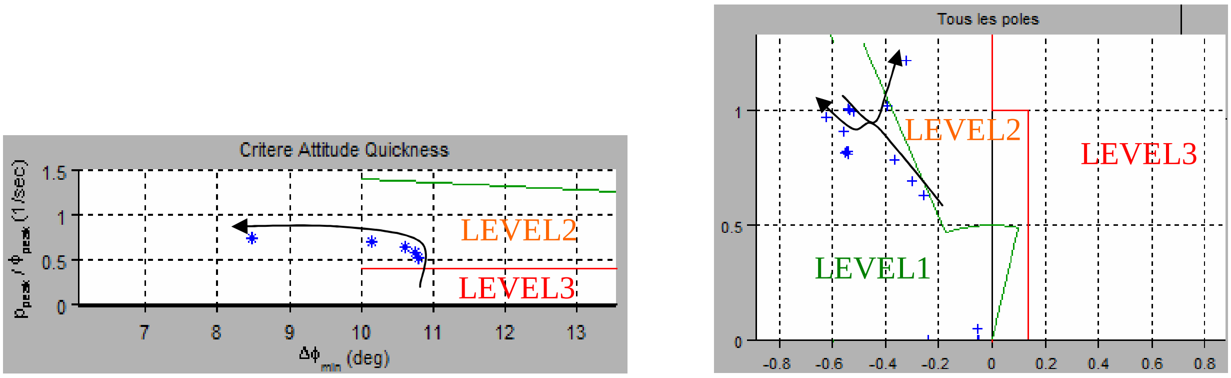
(a) (b)

Figure 8: (a) Influence of gain modification on stability for fast modes (almost no impact). (b) Influence of the same gain modifications for slow modes. $K_{i\theta}$ and $K_{i\psi}$ have been modified too.

3.1.4 Improving agility with good stability

Thanks to the first steps, we have found a configuration that take into account the authority available and the requirements of LEVEL1 stability. Now, we can try to optimize the attitude quickness.

First, the derivative gains should be used to ease the time response of the system, which means the system will be less agile. However, reducing the values of the derivative gains will reduce the stability of the system too. A compromise must be done there, and the eigenvalues' plot is useful for this step. The Figure 9 shows this tuning. We can see that a value of $K_p = -0.2$ is still interesting here.



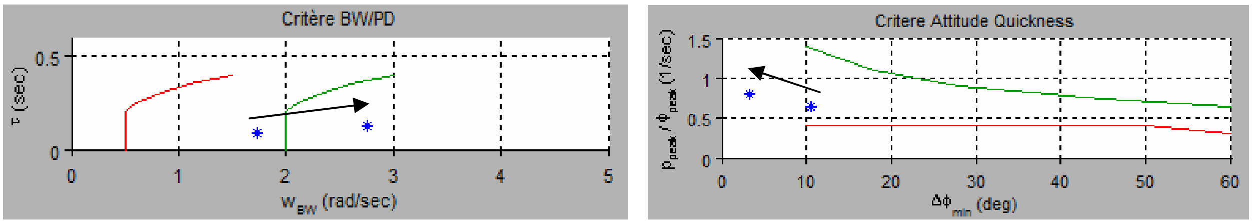
(a) (b)

Figure 9: (a) Impact of modifying the derivative gain from -0.4 to 0 by 0.1 steps. (b) Influence of the same gain modifications on stability.

Then, we look for an optimum for the integral gains which reduce the steady-state error, and also have an impact on the minimum and maximum attitude change used for this criterion. In all cases, we must keep in mind to keep the system stabilized, as much as possible in LEVEL1. We can also modify slightly the proportional gains in order to keep using the whole capability of the actuators. Once this is done, we can record the obtained configuration for further analysis: this configuration has been made to optimize the attitude quickness, taking into account stability and actuators saturations requirements.

3.1.5 Improving precision with good stability

This step consists in studying the bandwidth / phase delay criterion. The associated calculations used are non-linear (using logarithmic and minimum functions), and even with the help of the tool, it is quite hard to find tendencies in the sensitivity. Whatever the modifications are, we must keep the system stabilized and use no more actuators authority than available. However, a configuration has been found to optimize this criterion, but the modifications have a big cost on the attitude quickness. The Figure 10 shows this. Once we have done this, we can record the new configuration optimized for the bandwidth / phase delay criterion.



(a) (b)

Figure 10: (a) Best configuration obtained for the BW/PD criterion. (b) Unwanted impact of optimizing the BW/PD criterion on the attitude quickness.

3.1.6 Compromises between all constraints

The Figure 11 shows the final configuration chosen to make compromises.

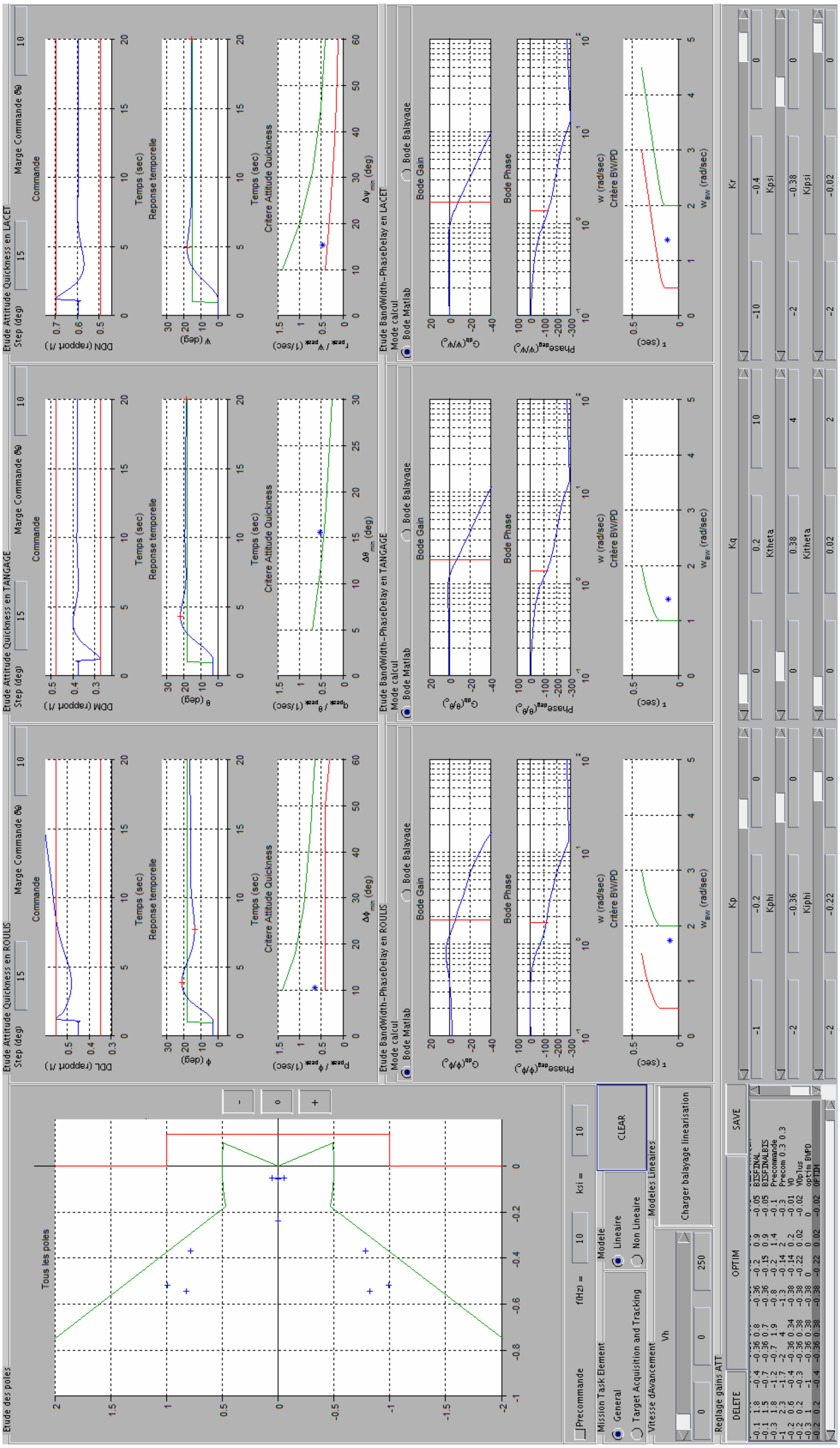


Figure 11: CAST-HEL-AP with the final design.

3.2 Resulting considerations useful for making new designs

3.2.1 Summary of the results

Table 1 summarizes sensitivity tendencies we have found after making our designs. We specify in each cell the sensitivity of the gain of the line to the criterion of the column. We can remark that compromises have to be done between agility and precision (last two columns) for the derivative and integral gains. **The first column specifies the last configuration chosen for our final design** and the curves shown on Figure 11 have used this configuration (and can be compared to the starting design shown on Figure 5).

Table 1: Summary of results of our design

If we increase the absolute value of:	Needs from actuators	Poles		Attitude Quickness	BW/PD
		Slow modes	Fast modes		
$K_p = -0.2$	No valuable impact	Stabilization	**Destabilization**	**Deterioration**	**Optimum -0.3**
$K_q = 0.2$	No valuable impact	Stabilization	**Destabilization**	**Deterioration**	**Optimum 1**
$K_r = -0.4$	No valuable impact	Stabilization	**Destabilization**	**Deterioration**	**Optimum -1**
$K_\varphi = -0.38$	**Saturation**	Stabilization	Very slight destabilization	Big improvement	Improvement
$K_\theta = 0.38$	**Saturation**	Stabilization	Very slight destabilization	Big improvement	Improvement
$K_\psi = -0.38$	**Saturation**	Stabilization	Very slight destabilization	Big improvement	Improvement
$K_{i\varphi} = -0.22$	Slight increase	**Destabilization**	No valuable impact	**Optimum -0.22**	**Optimum -0**
$K_{i\theta} = 0.02$	Very slight increase	**Destabilization**	No valuable impact	**Optimum 0.02**	**Optimum 0**
$K_{i\psi} = -0.02$	Very slight increase	**Destabilization**	No valuable impact	**Optimum -0.02**	**Optimum -0**

3.2.2 Interpretations and discussion

The following remarks have to be formulated after this design:

- Slight modifications of gains on one axis have almost no impact on the stability and precision criteria of the other axes (till stability remains good). The **cross-coupling** seems to be **negligible** for **attitude quickness and bandwidth / phase delay optimizations**, in the condition of having a good general stability.

- The collective input is abandoned to the trim during attitude capture simulations used for attitude quickness calculations. As a consequence, the helicopter leaves quickly its equilibrium status. To meet a new equilibrium state during the attitude changes and improve the quality of attitude captures simulations, **it's advised to add collective adjustments (with a feedback)**, which should improve the **stability of the helicopter and the quality of attitude changes**.

- The tool has not still integrated the cross-coupling, criteria of ADS standards. This improvement should be introduced in a future version of the software.

- During the first designs, it seemed impossible to meet the LEVEL1 handling qualities for all criteria. It was found that the HQ targeted values were too high. Reducing these objectives permitted to achieve a good compromise between stability, agility and precision. **The best we can do is to optimize the whole set of criteria**.

- The **time gained** using this tool is consequent. Without such a tool, a similar study could take days of adjustments. Here, the study was done in less than one day.

4. Conclusions and perspectives

The first stage of this PhD thesis has permitted the development of CAST-HEL-AP, a tool dedicated to the design of helicopter Flight Control Systems specified with strong requirements on handling qualities. The first application of the tool during the development of an Attitude Hold controller also permitted to define a first strategy of gains tuning. This first controller is being transferred to the ONERA Prototyping and simulation platform “PycsHel” for piloted evaluations (Figure 12).

The trends observed on the criteria sensitivities to the gains are currently being studied with a full non-linear flight dynamics model (HOST – Helicopter Overall Simulation Tool) and physical and theoretical considerations are accompanying this work. The final aim is to provide the most appropriate methodology to accurately tune the Flight Control Systems in accordance with the handling qualities criteria. The final focused application is for ship landing operations.

(a) (b)

Figure 12: (a) Earlier version of PycsHel. (b) Current, in-development version.

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