DESIGN METHODOLOGY OF FORCE FEEDBACK LAWS THROUGH HELICOPTER CONTROL LOOP SIMULATION

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Abstract

The latest evolution of pilot controllers, referred to as ASSU (Active Side Sticks Units) provides static and dynamic tactile force (or haptic) feedback to the pilot at the grip. Combined with FBW (fly-by-wire), this promising technology has enhanced safety levels compared to the original mechanical linkage systems they have started to replace, while offering vast improved benefits in terms of carefree handling and pilot situational awareness.
In the framework of a PhD thesis, the Information Processing and Systems Department (DTIS) of ONERA and SAFRAN Electronics & Defense have started a cooperation to evaluate the interest and the different possibilities offered by the ASSU technology to improve safety and handling qualities of rotary wing aircraft.
Up to now, the design and tuning of these functions were essentially performed thanks to numerous simulator sessions or flight tests with pilots. More than just providing a set of values for the required parameters defining the cueing function (hopefully an optimal set of parameters), it is expected that the approach presented here would reduce the number of piloted simulation tests and associated difficulties of the availability of pilots, the significant amount of time and material resources. This paper describes the work done during the first half of the thesis.
The main objective of this work is to develop a design methodology based on the simulation of the entire helicopter control loop (also including the pilot in some form) and enabling the definition and parameterization of cueing functions.
Moreover, some objective criteria will be defined and used to design the force feedback laws, bringing additional means of evaluation and validation than the classical subjective rating scales.

Keywords

Helicopter ; Active Side-Stick ; haptic feedback ; simulation; flight envelope protection

Notations and acronyms

ACAH	Attitude Command Attitude Hold
(A)FCS	(Automatic) Flight Control System
ASSU	Active Side-Stick Unit
SS	“Soft Stop”
RCAH	Rate Command Attitude Hold
ATT	Attitude retention mode
SAS	Stability Augmentation System
TAS	True Air Speed
Vx	Longitudinal velocity
Vz	Vertical velocity
φ, ψ	Resp. bank and yaw angles (in Euler angular coordinates system)

1. INTRODUCTION

In the early days of aviation, aircraft control was based on the use of mechanical linkages between the flight control surfaces (ailerons, rudder for aircrafts, swashplate for helicopters) and the

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pilot's commands. The development of civil and military aviation, and the emergence of increasingly larger, faster and more agile aircraft, led to greater efforts on commands and the need of assistance systems. This is when hydro mechanical controls appear: the mechanical linkages are now connected to actuators to move the different control surfaces. This system represented a cost of maintenance too important for the civil aviation, which made the mechanical linkages to be replaced by electrical wires, and the actuators by servo-motors. Nowadays this technology, known as "fly-by-wire", is used on the most popular commercial transport aircrafts.
Aircraft manufacturers have followed different trends concerning the pilot's commands, offering each one different benefits. SAFRAN Electronics & Defense (E&D) is currently working on the maturation and development of its own Active Side Stick Unit (ASSU). This arising technology offers:
• Better ergonomics, offering a clear view to flight displays;
• An ability to restore static forces lost with the transition to the "fly-by-wire" commands; and generate dynamically different haptic feedbacks. Combined with a monitoring of different flight variables, these haptic cues can, for example, prevent the pilot of approaching critical flight situations like entering stall [1] or Vortex-Ring State [2].

A lot of studies have already shown that using ASSUs and dedicated haptic cues are numerous:
• A pilot workload reduction and situational awareness improvement;
• An improvement of the flight envelope safety;
• Better performances of the aircraft, since the pilot can apply frank instructions;
• An electronical coupling of the pilot's and co-pilot's command inputs.

The ASSUs offer the possibility of generating forces in the grip which can be felt by haptic sense of the pilot. These forces can be programmed to vary with time, angular position of the grip, aircraft state variables, aircraft/helicopter limitations and other parameters that are related to the flight envelope security. This set of forces defines the static characteristics of the ASSU, and can be decomposed into a combination of elementary "feel modules", such as softstops (SS), detents, gates, friction, vibrations, all of these in addition to the baseline linear force-displacement law (see Figure 1). The gradient (slope) of this nominal curve will be referred to as the Q-feel (QF) parameter, as denominated by some manufacturers.

We also use dynamic parameters to refer to the damping ratio and the response frequency of the ASSU (as explained later, the ASSU emulates the behaviour of "classical" mechanical sticks or yokes, so its controller drives it to behave as a physical, linear second order system mass-spring-damper).

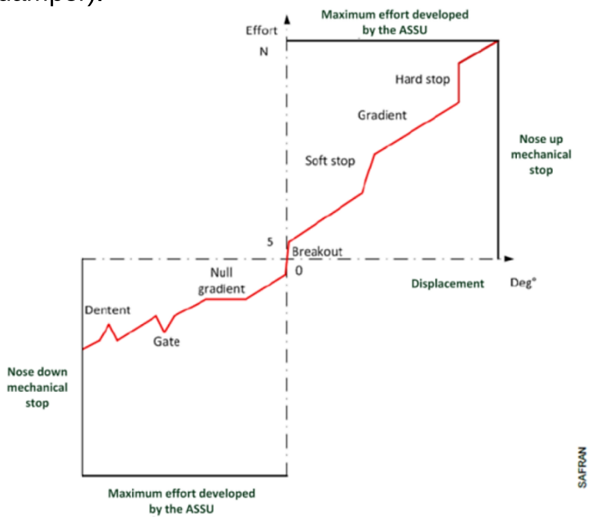

Figure 1 - Static Force/Displacement curve showing different type of force feedbacks.

SAFRAN E&D wishes to highlight the performance of its active stick with the demonstration of the capabilities of this new haptic feedback technology. Thus, in the framework of a PhD thesis, the Information and Systems Processing Department (DTIS) of ONERA-Salon de Provence and SAFRAN E&D have started a cooperation to evaluate the interest and the different possibilities offered by the mini active sticks in order to improve the safety and flying qualities of rotary and fixed wing aircraft.

More specifically we aim to bring focus on the following problematics:

- What are the different use-cases in which a mini-stick can offer piloting assistance and protection of the flight envelope?
- How to define, ab initio, or in an optimal way, the haptic cues and integrate them in the control loop?

A state of the art has been done to understand the advances made on this subject, and to evaluate the different possibilities to answer these questions. So far, to our knowledge, there is a lack of formal methods for defining haptic cues, other than simulator experimentation with pilots and with a more-or-less empirical approach. Thus, we will seek through this thesis to:

1. Develop tools and define criteria that will allow the specification of optimal force feedback laws.
2. Model a complete simulation loop to evaluate the haptic cues defined from these criteria ;

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It is expected that this approach will help the development and testing of haptic cues, by reducing the number of simulator trials.
Thus, the following sections will describe the work carried out to develop this simulation/evaluation environment of haptic feedback laws, and more precisely focus on:

- The complete helicopter control loop simulation setup, comprised of Functional blocks: Helicopter flight mechanic code – RCAH augmented control law – Active side-stick model – guidance module – pilot activity model – cueing algorithms);
- The development of a pilot activity model, integrating tactile sensitivity to take into account the cueing function while performing a prescribed piloting task;
- The operational test case setup and cueing function design;
- Preliminary developments of a behavioural logic to apply during a piloting task, depending on the goal of the cueing function (Guidance/Envelope protection function)
- The analysis of the results

2. OVERALL OF THE SIMULATION LOOP

The objective of this thesis is to develop a methodology to design a cueing function for given test cases. This design methodology is based on the simulation of the complete helicopter control loop which can be broken down into different functional blocks as shown in Figure 2.
This haptic evaluation loop should allow, ab initio, the (optimal) specification of the different ASSU's parameters from the definition of performance criteria such as the correct completion of a piloting task or the non-exceedance of flight parameter limits. Thus, a complete helicopter simulation control loop has been developed, integrating a module of the dynamics of each element, namely the flight mechanics of the helicopter, the behaviour of the ASSUs, and a pilot activity module (Figure 2).

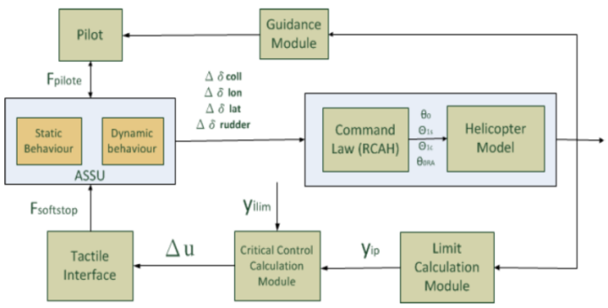

Figure 2 - Complete simulation loop for haptic cueing design

2.1. Helicopter flight mechanics code

The helicopter dynamics are provided by the full non-linear flight mechanics code FlightLab, developed by Advanced Rotorcraft Technology. The helicopter model used is an OH-6A model (single-engine light observation helicopter) [3].

2.1.1. Augmented control laws (RCAH) and AFCS modes

Several FCS modes can be selected on different axis (ATT, SAS, Vx/Vz hold). An augmented RCAH control law has been adapted to the OH-6A helicopter model used in this study.

2.1.2. Active side-stick model

The ASSU model reproduces the behaviour of classical sticks (dynamic response) and moreover, it offers the possibility of generating a compound force gradient called softstop (see Figure 1) on the grip, which can be adjusted to vary with time and aircraft state variables.

The first objective of an active side-stick is to reproduce the response of "classical" mechanical sticks or yokes. A mass-spring-damper system is then generally accepted as a model of the ASSU. Therefore, the active stick can be modelled by a force input position-output system of second order for each one of its axes:

$$\textbf{(1)} \quad \frac{x}{F_{pilot}}(s) = \frac{1}{K}\frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n}$$

where F_{pilot}(N) is the force exerted by the pilot to move the stick, x (deg) is the displacement variable corresponding to the position of the stick[1], ω_n (rad/s) is the model eigenfrequency, K (N/deg) is the spring's stiffness of the system, ξ (no unit) is the damping and s is the Laplace operator. This model structure is implemented by default on the ASSU controller.

2.1.3. Guidance module

A guidance module, which allows the transmission of pilot instructions in terms of flight parameters (for instance, hold an inclination angle or a

[1] If x corresponds to an angular deflection of the stick, then it would be more correct to express F_{pilot} as a torque, rather than a linear force. However, most of the manufacturers and publications make the implicit conversion by multiplying/dividing by the grip length (lever arm) when necessary.

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forward speed). This module will be improved in future developments, enabling more complex piloting tasks.

2.1.4. Cueing algorithm module

The model includes, in the feedback loop to the stick actuators, a cueing module allowing the computation of the parameter to be limited, and its conversion into flight "desired/prescribed" commands presented to the pilot via the ASSU.

As this will be explained later, the first cueing function chosen for the modelling of the simulation loop was the limitation of the bank angle to cue the pilot to limit φ to a maximum prescribed value. The helicopter model being "augmented" with a RCAH (Rate Command Attitude Hold) control law, the stick positions directly controls the angular speeds a.k.a. roll rate and pitch rate. An automatic turn coordination (in order to cancel sideslip) has been added.

The Haptic Module provides the force feedback law to be generated on the stick and its definition remains one of the main objectives of this thesis. Among all potential haptic feedbacks, the softstop is certainly the most appropriate to indicate such a limitation, because the pilot has to keep the ability to overcome the force cueing if he ever needs to (e.g. for an emergency avoidance or recovery maneuver).

It has been decided to generate a softstop on the cyclic lateral axis to, at least, warn the pilot of the roll angle limit, and hopefully to prevent any exceedance. The main objective is then to find, through this offline simulation loop, the characteristics of this softstop (amplitude, gradient).

The cueing module has to compute the position of the softstop. Thus, the equation below provides the maximum pilot command in lateral control axis δDDL0 before reaching the maximum roll angle value φmax,

$$\textbf{(2)}\quad \delta DDL_0 = \sqrt{\frac{2c\Delta\varphi}{\varphi_{\max}}}$$

where c is the softstop return speed to neutral position, and $\Delta\varphi$ the difference between φ_{max} and the current helicopter bank angle φ.

2.2. Pilot Model

The design of a pilot activity model has been undertaken. This pilot model has to be able to follow a prescribed trajectory, or a piloting task, while being acting on the ASSU second order model and potential haptic force feedbacks, as well as controlling a full non-linear helicopter model with augmented control laws.

For the "piloting" task, a precision pilot model, proposed by McRuer [4], has been integrated. It provides a list of some aspects of human behaviour, hereby modelled as a transfer function between a piloted output variable and a reference input variable (e.g. a target to follow). This model adds the neuromuscular dynamics of the pilot to the well-known crossover model:

$$\textbf{(3)}\quad Y_p Y_c = \frac{\omega_0 e^{-\tau s}}{s}$$

where Y_p and Y_c are respectively the pilot and the aircraft transfer functions, ω_0 is the (open loop) crossover frequency, and τ the transport delay time caused by the pilot neuromuscular system.

3. SENSIBILITY EXPERIMENT

Since the goal of the study is to determine cueing function parameters based on this complete simulation loop, it is also necessary to provide to the pilot activity model detection criteria so it is able to take into account the presence of a force feedback. It is expected that the shape of the force feedback (amplitude, force gradient, position, etc.) will change the way it is detected, and thus will have an impact on the realization of the piloting task and/or on the limitation of some flight parameters, etc.

An experiment was set up on the PycsHel helicopter prototyping and evaluation simulator at ONERA [5] to assess the force detection thresholds of actual pilots on the ASSU (see Figure 3 and Figure 4).

Figure 3 – The CAVE configuration of the PycsHel simulator at ONERA Salon de Provence

The data obtained were analysed with statistical methods adapted to the study of ASSU's parameters. While only roll-axis was tested, some insight about the effect of ASSU's parameters on the haptic detection has been obtained.

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Figure 4 - the ASSUs used respectively as collective stick (left) and cyclic stick (right).

3.1. Experimental protocol

The subject was instructed to perform a simple flying task, where he would have to follow the position of a target located at a fixed distance in front of him (i.e. moving at the same forward speed as the helicopter), and moving randomly up and down along a vertical axis. The subject controlled the vertical motion of the helicopter through the collective stick, and a projection of its altitude was given in order to evaluate the relative positioning error. Meanwhile, the subject was also instructed to move the stick laterally from left to right, and back, and to press the stick trigger whenever he encounters a softstop during the sweeping motion. Actually, the objective of the vertical tracking task was to ensure that the subject was not too precisely focused on the detection of the SS, similar to how an actual pilot would be engaged in a more or less complex, multi-tasked and cognitively loaded flying activity.
A simplified, linearized model was used to simulate the lateral flight dynamics of the helicopter. The forward speed was kept constant, while the vertical motion was highly damped, in order for non-pilot / non-expert subjects to run the task.

Parameter	Values
Frequency $\omega_n/2\pi$	[3 ; 5] (Hz)
Damping ξ	[0.5 ; 0.75 ; 1.25]
QF	[0.5 ; 1 ; 1.25] (N/deg)
Motion speed	[slow ; fast]
softstop amplitude	[3 ; 6 ; 9] (N)
softstop position	[±3 ; ±7 ; ±10 ; ±14] (deg)

Table 1 - Summary of ASSU and softstop parameters tested.

A total of 6 sets of softstops combinations were tested in which the frequency or damping of the ASSU model is modified (Table 1). A total of 6 subjects performed all the sets, preceded by a familiarization phase. Each one of the sets consists of 144 combinations of SS randomly distributed and repeated 3 times.

3.2. Overview of results

A multiple linear regression was attempted in order to predict the force applied by the pilot at the moment of the SS detection, as a function of the different haptic and ASSU's parameters. However, so far no significantly enough representative regression model based on the force has been obtained, which could led to the conclusion that the force detection as a function of the different ASSU's parameters do not follow a linear law.

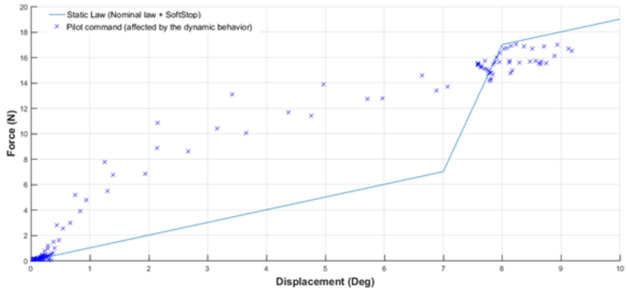

Figure 5 - overshoot generated, in comparison with the linear law, in response to a command with the ASSU.

On Figure 5 we can observe how the response (deflection) of the stick to a pilot force input differs from the linear static law in the presence of a softstop, this dynamic behaviour being more significant as the force introduced by the pilot is important. In addition, it can be seen that the stick is unable to stop its motion while traversing the softstop.
This can be easily explained when looking at the indicial (step) response of a 2nd order system for different values of the damping coefficient, as seen on Figure 6 below.

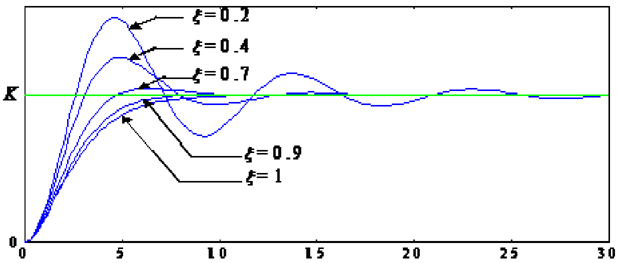

Figure 6 - Step response of a 2nd order system.

This undoubtedly affects haptic detection, since the pilots could detect the force gradient variation at different points, or even "fly over" the softstop without noticing it. This behaviour is not noticeable with the SAFRAN's ASSU, since it uses control laws which prevent overtaking without generating an important position lag. This control laws regulates the damping and inertia intervals which allow a stable use of the ASSU.
Future experiments led with this system should provide more repeatable and consistent results.

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Damping= 0.75, Frequency= 3, QF=1, Slow Speed								
Amp \ Pos	-14	-10	-7	-3	3	7	10	14
3	2.29	1.70	1.26	5.50	3.77	2.26	2.31	2.25
6	4.68	3.05	3.14	5.02	5.23	4.39	4.87	4.25
9	4.18	4.57	4.74	6.51	7.04	5.06	3.89	4.13

Table 2 - Mean force trends as a function of amplitude and position of the softstop for different sets of damping, frequency and static force gradient (QF).

The Table 2 summarizes mean force detection for a given set of ASSU's parameters where it can be shown some of the trends:

- Greater overruns on positions close to the neutral (±3°) and a tendency to stabilize the detection force average for the other positions.
- Greater efforts with increasing SS amplitude

According to these results, it was concluded that:

1) Pilots are sensitive to **force gradient variations**, since subjects have shown better detections with little gradients of the nominal law (QF=0.5). Little QF values have also shown to be more sensitive to high speeds, leading to a higher number of overtaking. A good compromise could be a QF value of 1.

2) Pilots are sensitive to **ASSU's damping**. Sets tested with high damping values have proven less SS's detection because it implies the arm's muscles to be contracted. On the other hand, higher damping values improve precision during helicopter's command and avoid overtaking the SS during high speeds. A good compromise could be a damping value of 0.75.

3) **Softstop's positions** influence on their detection. SSs positioned outwards have been more detected than SSs placed inwards. This could be explained physiologically by the well-known fact that we are stronger on inward (pronation) movements, and thereby less sensitive. Subjects also avoided confusing furthest SS with the mechanical stop. At furthest positions, the subject needs to apply a highest force, which implies a tension on the arm's muscles and a worse sensibility to force gradients. Additionally, SSs placed near the trim position presented less detection, which can be explained by the second order dynamics of the system. In fact, during rapid force inputs the response of the system deviates from the linear static law. Moreover, a breakout force (to avoid any stick displacement due to small/unintentional applied force) is generally placed at the stick trim position, needing an additional force to initiate the stick.

4. SENSIBILITY MODEL

4.1. Tactile sensitivity model

The results of the previous experiments were used to define preliminary detection criteria which were integrated in the pilot activity model.

Figure 7 shows a simulation reproducing the experiment, where the pilot model was instructed to stop moving the stick exactly when the softstop was detected.

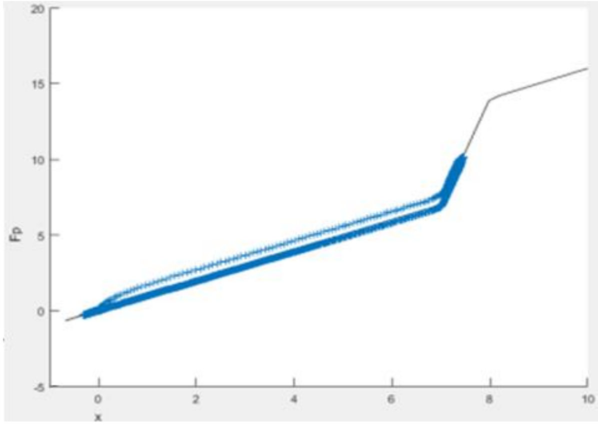

Figure 7 - Softstop static Force/Displacement curve and detection.

The conclusions obtained about pilot haptic detection were used to modify the pilot activity model in order to adapt the pilot model behaviour if any softstop appeared. More specifically, we used the result 1), according to which pilots would be sensitive to force gradients, defined as the instantaneous derivative of the applied force w.r.t. the stick position: $\frac{\partial F_{pilot}}{\partial x}$

As long as the pilot stays on the nominal (pre-softstop) law, the value of the above quantity is constant and more or less equal to the QF value (the difference being explained by the dynamical component of the response, as explained in the previous section).

However, if the pilot encounters a softstop, this gradient value increases. As a consequence, a first attempt to introduce a simplified detection model could take the form of a gradient threshold $\left(\frac{\partial F_{pilot}}{\partial x}\right)_{thr}$ with a reaction time. The determination of the value of this threshold will be the objective

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of one of the future experimental evaluations using the ASSU developed by SAFRAN E&D.

Once a change in the ASSU feedback has been detected (e.g. the occurrence of a softstop), the compromise between the piloting task to achieve and the presence of the haptic cueing has to be considered through an adequate behavioural logic.

4.2. Logic behaviour

This human and behavioural logic has to be taken into account into the pilot model if we want to be able to predetermine the haptic cue parameters through a simulation loop.
As a consequence, we have decided for initial evaluation purposes to define the simplest objective for our Pilot Model: maintaining the command around the detection point. This will clearly have an impact on the task-related performance criteria; but not only. The piloting law used (RCAH, ACAH, or direct law), the pilot's model dynamics (through the gains of the transfer functions), or the (static and dynamic) response of the ASSU should modify the pilot's performance as well. On the other side, when the pilot considers to have reached (or exceeded) his piloting instruction, it can move the grip away from the detection point and bring it back to neutral point (or to the opposite side).
Obviously, a pilot model could not be programmed to reproduce a unique, deterministic controlling action (what any pilot will do), but would rather have a certain variance, so as to reproduce a behaviour envelope sufficiently wide (what some pilots may do).
Some preliminary hypothesis will be set in the simulation loop, but will have to be confirmed or invalidated through exploratory simulator tests with pilots.
These different logics will be developed and adapted by means of the completion of an operational test case as described in the following chapter.

4.3. Consequences of ASSU's parameters on the Tactile Sensitivity Pilot Model

To illustrate the influence of ASSU's parameters on the tactile sensitive pilot model, the next figures show the difference on the performance achieved by this pilot model for a simple roll task. For this flight task, a Rate Command Attitude Hold is used in the lateral axis and a roll instruction of 20° is asked to the pilot without the help of any cue. The Figure 8 shows how a pilot model with average gains performs the task with a "human" precision. To evaluate how the different ASSU's parameters can affect the performance of this task, a function which limits the roll angle to 16 ° has been integrated in the task. Two softstops of 3 N and 9N amplitude indicated the position of the roll angle limitation to the pilot model, leading to different task performance as shown in Figure 9.

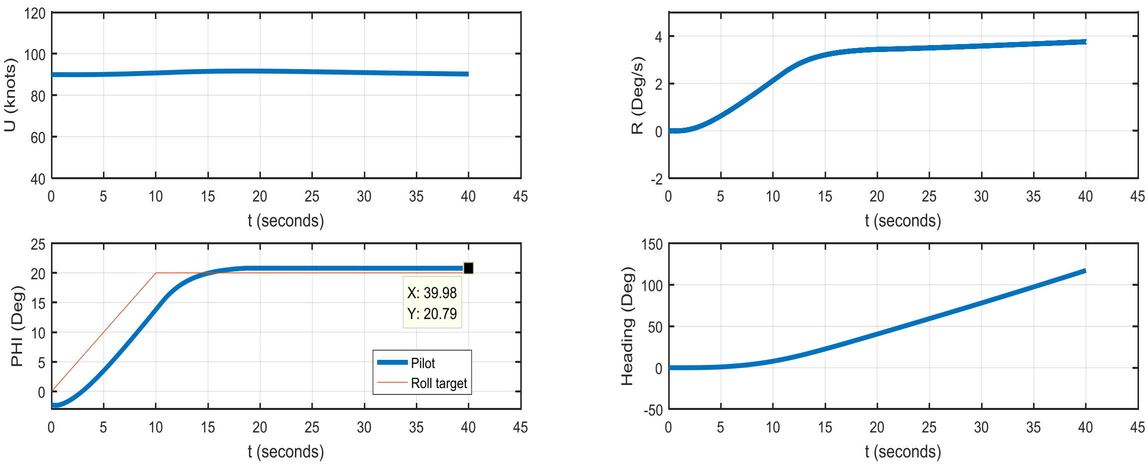

Figure 8 – Pilot performance for a roll intruction of 20°.

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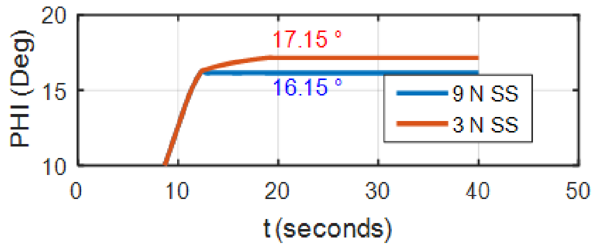

Figure 9 – Pilot performance to the roll angle limitation of 16° and for two different sofstop amplitudes

Other than tactile cue's parameters, ASSU's parameters as the damping, the frequency or the nominal law gradient (QFeel) can also modify the performance of the task. Again, a roll instruction of 20° is asked to the pilot without the help of any haptic cue (Figure 10).

This time, the QFeel is changed from 1 N/° (in blue) to 2N/° (in red), leading to an overshoot in Phi (°) of 1.5 ° and a delay of nearly 10 seconds. This difference is also observed in the command applied by the pilot model, as the pilot needs to apply more force to move the grip (Figure 11).

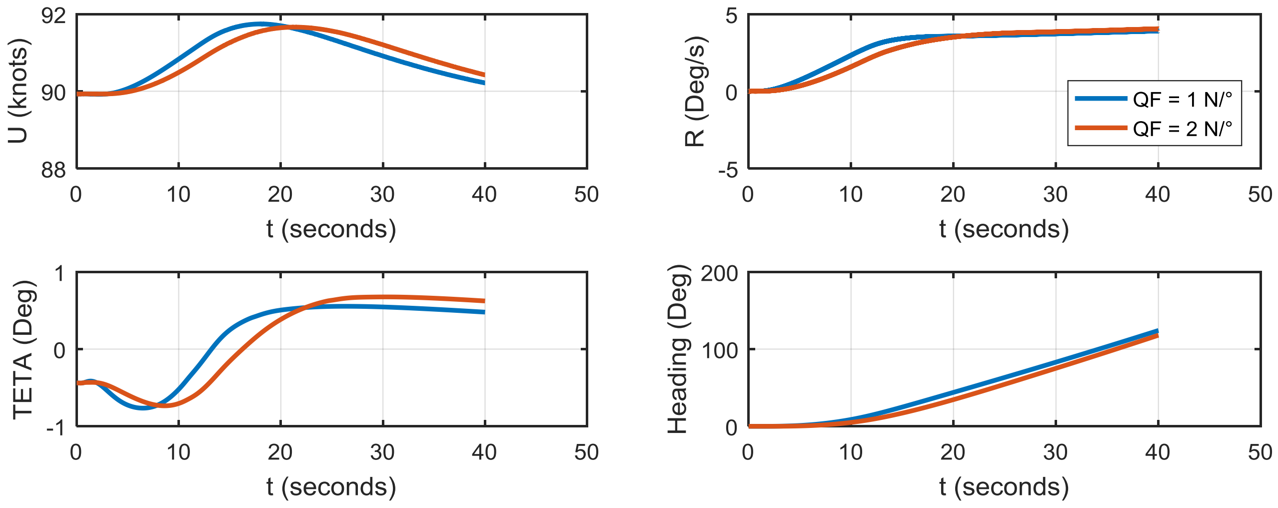

Figure 10 - Pilot performance for a roll instruction of 20° and with two different nominal law gradients of 1 N/° and 2 N/°.

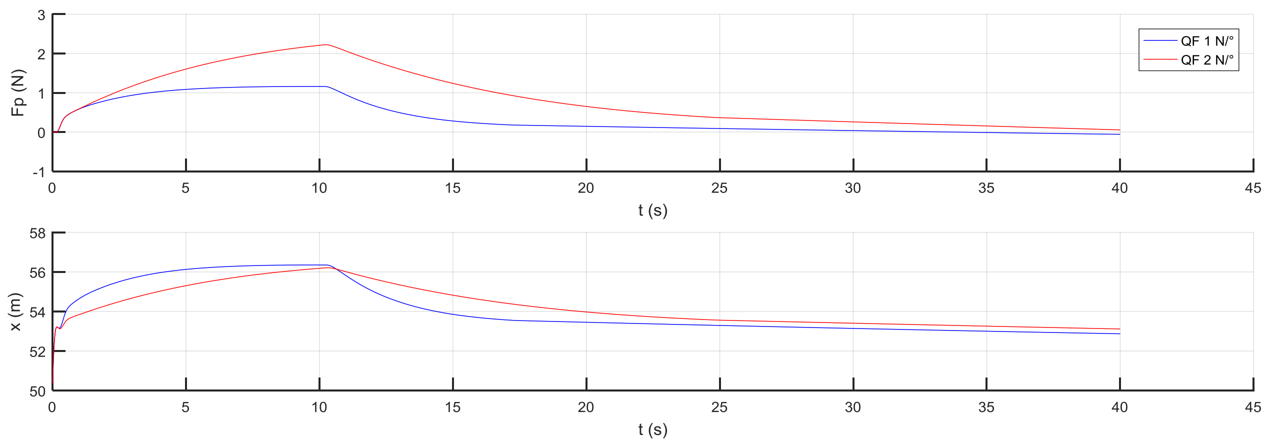

Figure 11 - Pilot command for a roll instruction of 20 ° and with two different QF 1 N/° - 2N/°.

Even if quite similar performances, the command to achieve the task with an equal level of performance can be quite different. Another criteria to be taken into account for the "design" of haptic feedback should be the pilot actions on the controls, as the force (Min/max), the power, or the frequency applied.

Therefore, the different parameters of a SS influence their detection and the results on the parameter to be limited (here Phi). Among the criteria to be taken into account for the "optimal design" of haptic feedback, the impact on the parameter should be taken into account, as the final or transient differences.

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5. OPERATIONAL TEST CASE

In order to validate the developed methodology, a first operational test case has been selected, consisting in a standard rate IFR turn. This task can be described as a 360° turn in 120 ± 4s (= 3°/s turn rate) with constraints on flight parameters as described in [6].

As previously described, a roll angle guidance algorithm has been setup to feed the cueing function, giving the reference roll angle as a function of yaw rate and airspeed. If we want to cancel the sideslip angle, the lateral flight equilibrium equations lead to

$$\textbf{(1)}\quad \varphi_{\text{command}} = \arctan\left(\dot{\psi}\,\frac{TAS}{g}\right)$$

Following the constraints, the pilot model receives an instruction to decelerate to 60 kts and to adapt accordingly the bank angle in direct control.

Two softstops, one in each side of the lateral stick trim, guides the pilot model through the exact indication of the ideal stick deflection to perform the maneuver $\varphi_{command}$. The pilot has first to find the softstop(s) position, then to continually "rest" against it. In the case where the pilot does not reach it, or exceeds it, the performance of the guidance function will decrease.
The dynamics of the pilot action in response to a moving SS have been modelled, especially when the SS is moving towards the pilot input, and when the SS passes to the other side of the stick trim position.

Since the current work concerns the definition of the appropriate haptic cue based on the optimization of objective criteria, this means, among other works, finding the haptic cue parameters, such as amplitude and force gradient for a softstop, that allow the best detection/recognition and following during a piloting task. The type of law commanded, on the axis where the haptic cue is placed, should also influence the cue parameters. For this reason, this roll angle guidance function has been tested on direct and RCAH law command.

5.1. Direct command

Figure 12 shows the IFR-turn achieved by the pilot activity model (blue curves) trying to follow the roll angle target (green curve) in direct command and by an Automatic Flight Control System (AFCS) command based on the calculated softstop position (red curves). Comparing both results in Figure 13 it can be seen that the "optimal" lateral position provided by the softstop (if it were used as an AFCS command), leads to a better performance in accomplishing the standard rate IFR-turn in the specified time. Thus, if the pilot could precisely detect and then follow the softstop, he would be able to improve its performance.

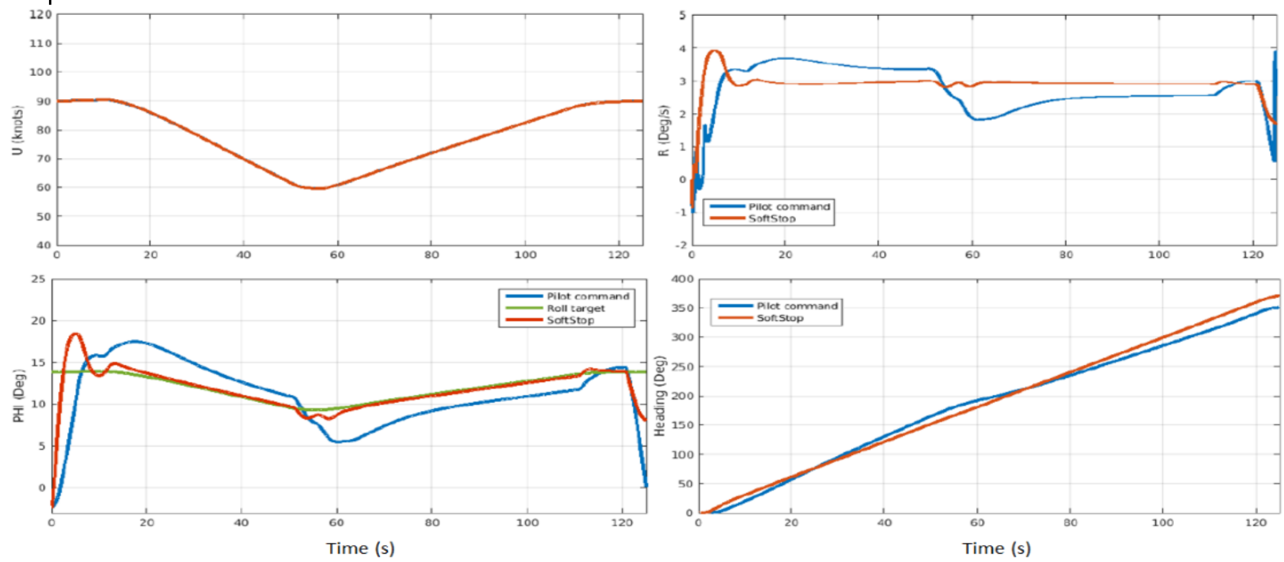

Figure 12 – Comparison of a standard rate turn performed by the pilot activity model and AFCS

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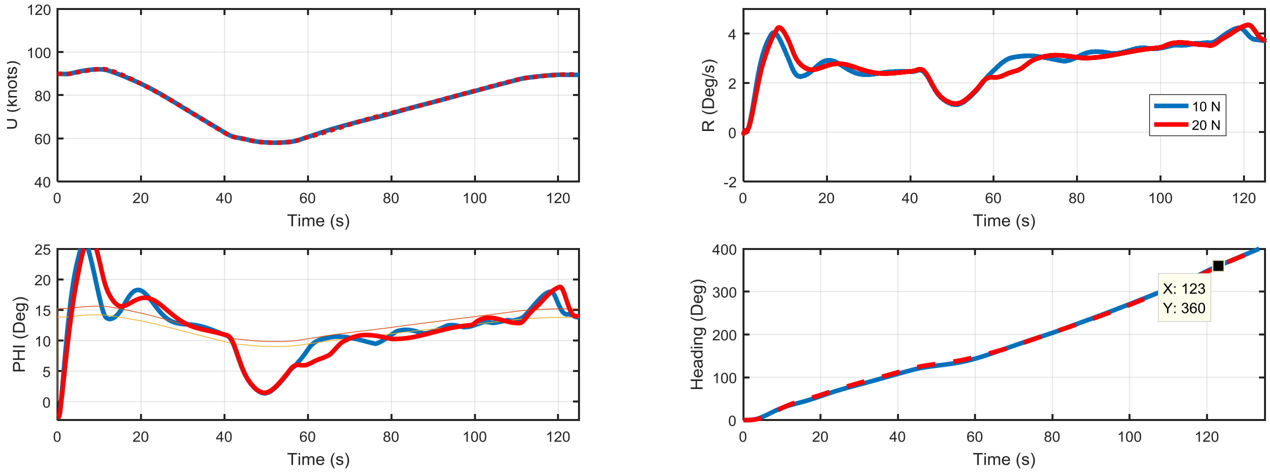

Figure 13 – Standard rate turn performed by the pilot activity model following SSs of 10 N and 20 N

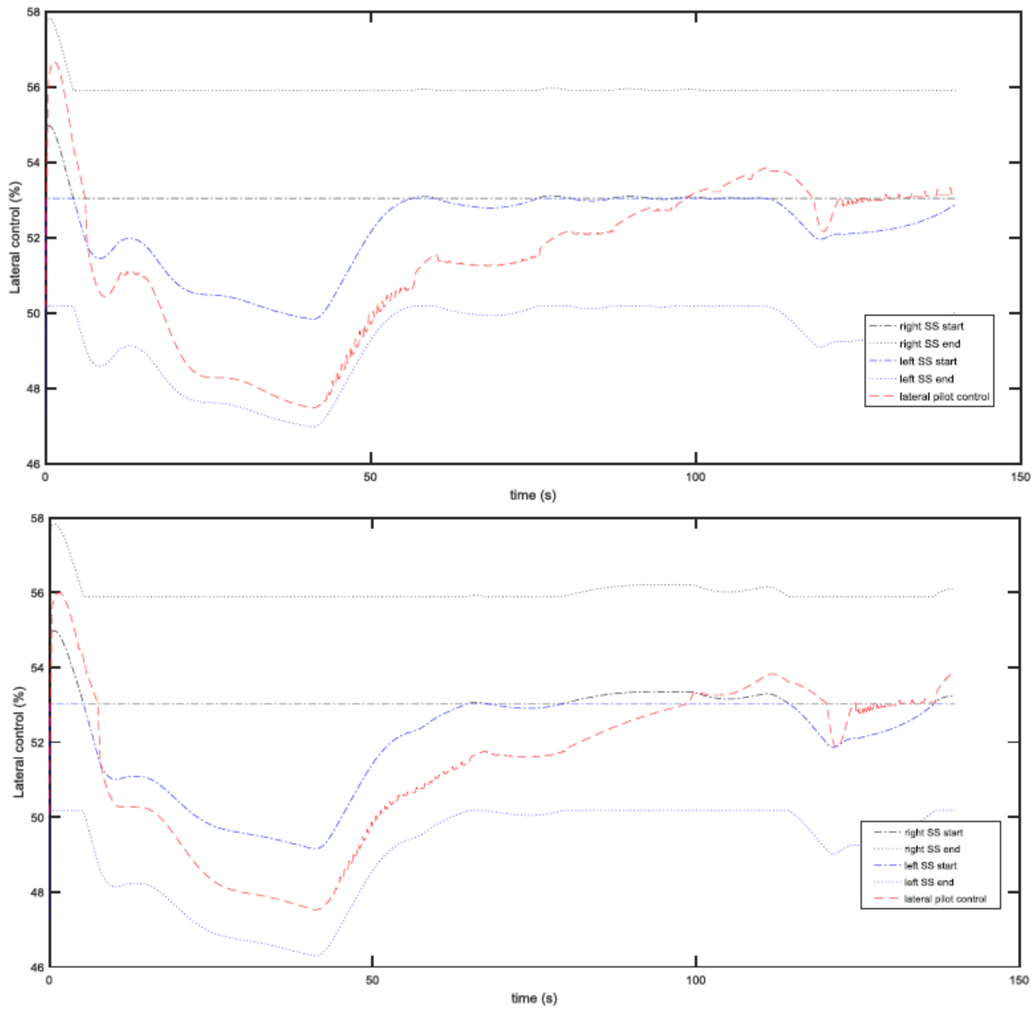

Figure 14 – Pilot lateral control for the stand rate turn task and with the aid of SS of 10 N/° and 20 N/° gradients.

Once the tactile sensitivity pilot model and the different logics have been integrated, it was interesting to compare the performance achieved by two different SS of 10 N/° and 20 N/° gradients. As expected, the pilot increased its performance when following the haptic aid and achieved the 360° in the correct interval (Figure 13). We can observe that even if the gradient has influenced the roll angle commanded, it does not have an effect on the standard rate turn.

Figure 14 represents the start and end positions of the right SS (in black), the left SS (in blue) and

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the lateral pilot command (in red). The roll target $\varphi_{command}$ is send through the SS in such a way that when $\varphi_{command}$ is over the trim (here around 53%), it is the right SS which moves to indicate the target to follow, and the left SS remains at the trim position, and vice versa. The first figure shows the pilot command when exceeding a 10 N/° gradient SS, the second one a 20 N/° gradient SS. We can observe that even if the 10 N/° SS is more exceeded (around 1%), the consequence of this does not have a considerable impact on the roll instruction (see Figure 13). The minor effect of changing the gradients of the softstops on the flight task is certainly due to the use of the direct control law in the lateral axis, for which commands deviations are smoothed by the flight mechanics.

5.2. Rate Command attitude hold (RCAH)

The same IFR standard rate turn has also been tested with the RCAH law. For that, the $\varphi_{command}$ calculated in Equation (4) is used as the maximum roll angle value φ_{max} in the Equation (2). Figure 15 shows the performance of the flight task of the pilot without any aid (in blue), the pilot with the aid of a 5 N/° gradient SS (in red), and a 20 N/° gradient SS (in yellow). Figure 16 represents the SSs positions and lateral pilot control of Figure 15.

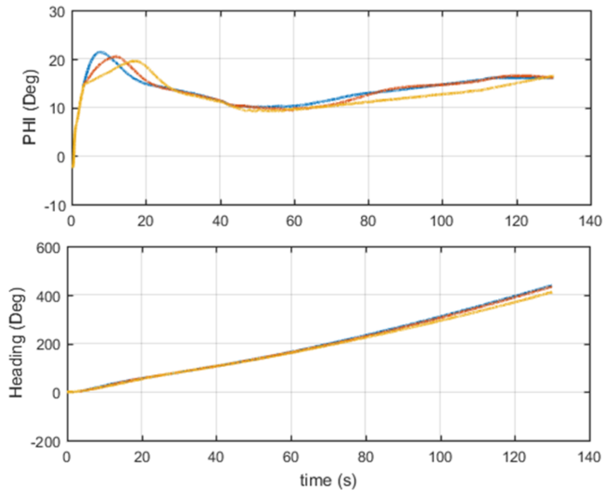

Figure 15 – Standard rate turn performed by the pilot activity model without SS and following SSs of 5 N/° and 20 N/°

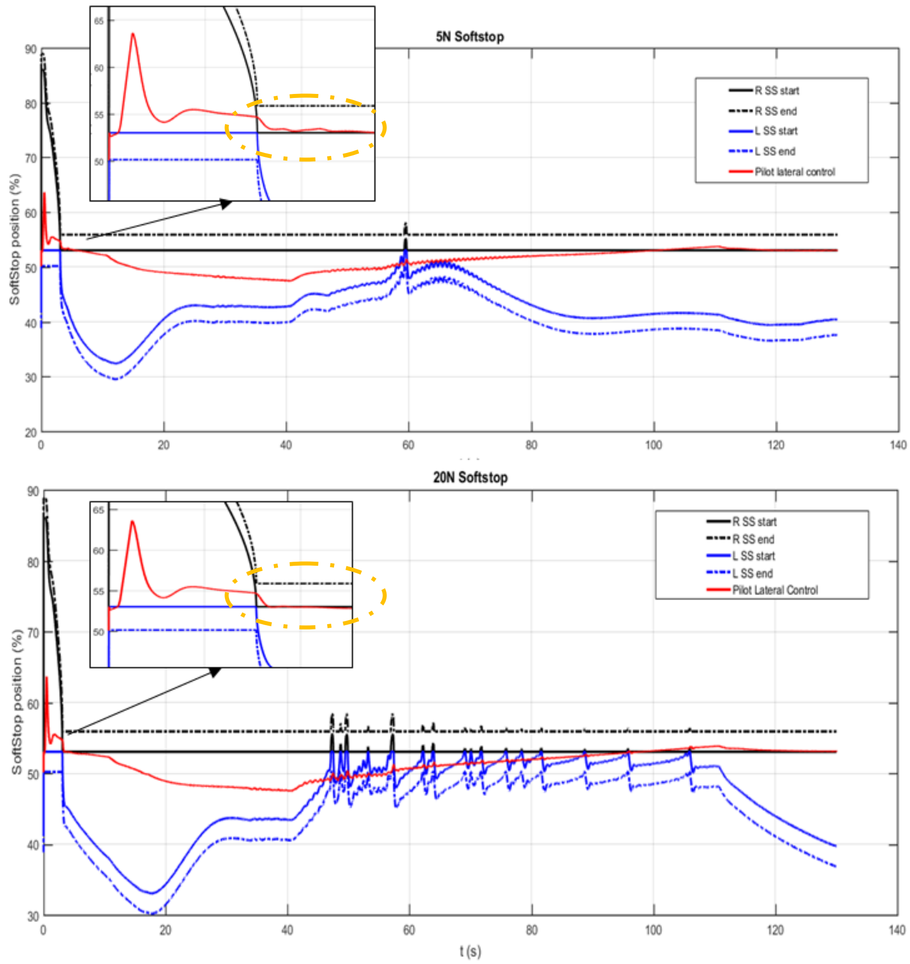

Figure 16 - Pilot lateral control for the stand rate turn task and with the aid of SS of 5 N/° and 20 N/° gradients.

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Analysing both figures, we can observe that 5 and 20 N/° gradient SSs modifies the command:

- At the beginning, the right SSs positions (start and end positions of the SS) are far from the pilot control, but at around t=4 seconds they moves to the trim to bring back the pilot. The detection logic, as based on the force gradients, generates a modification of the commanded roll angle, bigger for the 20 N/° than for the 5 N/° SS.
- Again, in the mid of the task, the left SS moves back to the pilot. There is a higher interaction between the pilot control and the 20N/° SS, leading to a better following of the prescribed roll angle.

6. DISCUSSION

The actual logic would require, once the right SS has reached the stick trim position, that the pilot applies a left stick motion to reach the left SS. This logic is probably not the most intuitive one; thus the SS positioning will be changed by introducing a variable stick trim position. Then, once the right SS reaches the trim position, it will follow the required SS position enabling the pilot to continuously "feel" the SS from the right.
While it can be seen that this model is able to capture and take into account the changes in the SS form, the impact on the flight mechanic and the prescribed parameters such as φ is relatively small. This can be partially explained by the fact that the 3 other axis here are precisely controlled by some AFCS modes.
In addition, the axis decoupling provided by augmented control laws such as RCAH limits the cross-axis couplings.
In real conditions, the pilot would have to follow the airspeed, the roll angle and maintain the altitude. This task would require a quite high workload, even using a RCAH law. The performances of a real pilot would certainly be lower than the ones presented here. That is why, in order to adapt the actual pilot activity model, a new experiment will have to be set up.

This IFR task will also be further used to evaluate the use of softstops for two different objectives:

- Guidance function: informing the pilot of the "optimal" stick command (Figure 12 to Figure 16).
- Protection envelope function: limiting the roll angle to a maximum prescribed value (as in Figure 8 to Figure 11)

In both cases, the logic to be used by the pilot activity model should be different such as the softstop shape.

7. CRITERIA FOR OPTIMIZING HAPTIC FEEDBACK

In order to analyse and compare the influence of the different parameters defining the softstop, a first set of criteria can be proposed:

- Simulation domain
  - Performance (task realization), ADS-33 (desired vs adequate)
  - Discrepancies between targets (φ_{command}) and performed parameter (φ_{pilot})
  - Limit exceedance (φ_{pilot}) compared to (φ_{limit})
  - Stick activity (mechanical energy, time-frequency analysis)
  - Biomechanical criteria (maximum power, maximal force, maximum rate…)
- Piloted evaluation
  - Cognitive workload ([7]).
  - Situational awareness
  - Pilot acceptance

The task performance criterion ψ_{end}, already used in the IFR standard rate application case, has been the first optimization criteria used (Figure 12). Other important criteria, as the command applied by the pilot, or the exceedance with respect to the guidance position (Figure 13) need to be considered to define the optimal haptic cue.
The comparison of the task performance, in direct and RCAH law commands, highlights the fact that the type of force feedback provided needs to be studied according the command law, or the goal of the haptic function.
In fact, softstops have proved to be the most effective to warn the approach of critical values or limit parameters, but they seem not completely efficient in piloting guidance. Adding a very smooth detent or changing the stick parameters once close to the haptic cue will be studied.
Hereafter, some comparison of different criteria for the two selected softstops (in RCAH law command):

Task performances:	**5N/°**	**20N/°**
Final Heading	*389.72°*	*369.56°*
Integral of error on PHI	*263.87*	*158.67*
Integral of error on R	*77.92*	*59.47*
Pilot activity:		
Integral of pilot force	*64.26*	*35.92*

Table 3 - Summary of the criteria applied to the twp different SS (5N/° and 20 N/°) for the standard rate task in the RCAH law.

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Considering the criteria presented here, it would be logical to opt for the 20 N/° gradient SS. Nevertheless, it is necessary to take into account subjective criteria which remain as important as those obtained from the offline simulation. The pilot's acceptance, or the experience and awareness of the task to be limited (or guided) must be valued during simulator experiments. For the cognitive workload, even if hard to estimate due to its personal character, recent work enables an estimation of it. These estimations should still be compared to experimental results.

8. FUTURE WORK

The next steps will focus on:

- Improving the detection in the Pilot activity Model of the full off line simulation loop. This might need another sensibility experiment able to provide detection gradient thresholds.
- Improving the different logics of the pilot activity model during the detection and following of the haptic cues. The different logics will certainly have to be modified depending on the type of haptic cue.
- Formulating the criteria for the performance evaluation of the pilot model (completion of the task, exceeding of the pilot instruction, activity on the grip, etc.).
- Identifying and integrating different biomechanical limits of the pilots (long term power, maximum punctual force, etc.) in the pilot activity model.
- Developing a "Multi axis" pilot model, capable of controlling itself the different axis and complete a piloting task, giving priority to certain flight parameters through a sequential process.
- Complete haptic cueing definition process through off-line simulation loop using dedicated criteria to define the "optimal" softstop. Then, this IFR standard turn task will be implemented in the real time PycsHel simulator and piloted evaluation will be performed to assess and hopefully validate the proposed haptic function.

9. CONCLUSIONS

- A full simulation loop integrating different modules, for the evaluation, analysis and optimization of haptic feedbacks, has been modelled.
- A tactile sensibility experiment in the PycsHel simulator has been set up to "provide" the pilot activity model with a tactile sensibility. This sensibility has been associated with some basic logics modifying the activity of the pilot when detecting a haptic cue. They will continue to be improved and modified depending the limitation or the guidance function evaluated.
- A pilot activity model has been developed enabling to follow prescribed piloting tasks and capable of adapting its piloting logic in the presence of haptic feedbacks. For that, a detection logic, based on the analysis of the required force to apply to the stick, has been developed and tested through offline simulations. Preliminary piloting logics have been developed and will be further mature thanks to piloted simulations.
- An IFR standard turn guiding function for the lateral axis has been integrated in the full off line simulation loop and tested with direct and RCAH law commands, allowing analyzing the performances achieved with the modification of SS parameters.
- A list of different evaluation criteria has been drawn, and the results should be analyzed soon for the haptic cue optimization. It seems clear that several criteria will have to be taken into account, based on task performances but also on the analysis of pilot activity. Depending on the task and the augmented control law, these criteria would probably have to be adapted.

If the preliminary results showed the ability of this approach to take into account the different forms of haptic feedback such as softstops, the complete process of defining a haptic function and its validation by pilots in simulator trials will be soon carried out.

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