Design methodology of force feedback laws for active side stick interface

Gemma Prieto Aguilar, Laurent Binet, Thomas Rakotomamonjy

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***Abstract*— SAFRAN Electronics & Defense and the Information and Systems Processing Department (DTIS) of ONERA have begun a cooperation to evaluate the interest and the methods of use of Active Side Stick Units (ASSU) to improve the safety and flight qualities of helicopters. This paper describes the work carried out to model an environment for simulation and evaluation of haptic feedback laws. An experiment, implemented in the simulator PycsHel at ONERA Salon de Provence, has brought some insight about the influence of ASSU's parameters on the detection of specific haptic feedbacks (Softstops). The results obtained will be added to the simulation model in order to allow the specification, optimal if possible, of the haptic cues.**

NOTATIONS

ASSU	Active Side Stick Unit
DDL	Lateral cyclic variation around an equilibrium point
HC	Helicopter
HQR	Handling Qualities Rating
QF	Gradient of the nominal Law
RCAH	Rate Command, Attitude Hold
SS	SoftStop

I. INTRODUCTION

In the early days of aviation, aircraft control was based on the use of mechanical linkages between the flight control surfaces and the 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 hydromechanical 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, what 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 advantages. SAFRAN Electronics & Defense (E&D) is currently working on the maturation and development of a new concept of pilot's command: the Active Side Stick Unit (ASSU). This new technology offers:

- A 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. These haptic cues can, for example, prevent the approach to the pilot of a critical flight parameter like the stall.

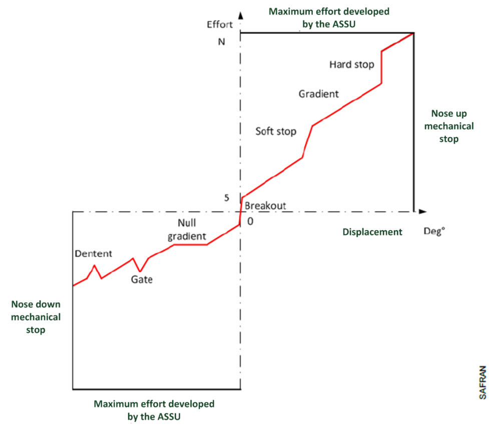

Fig. 1. Static law showing different type of force feedbacks.

The advantages 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 instructions without hesitation
- A coupling of the pilot's and copilot's commands.

The ASSUs offer the possibility of generating forces in the grip which can be felt by the pilot. These forces can be adjusted 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 by a combination of softstops (SS), detents, gates, friction, vibrations and the gradient of the nominal force-displacement law, or QF (see Fig. 1).

We also speak about dynamic parameters to refer to the damping ratio and the response frequency of the ASSU (as explained later, the ASSU emulates the behavior of

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"classical" sticks or yokes, so behaves as a physical, linear second order system mass-spring-damper).

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:

- What are the different fields 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. The main topics which can be found are:

1) *ASSU's Parameter setting*. Part of the literature dedicated to ASSUs has focused on studying the effects of the characteristics of the stick on the flight qualities of the aircraft. For example, [1], [2], and [3] studied the variation of the flight quality scales (or HQR, Handling Qualities Rating) as a function of the frequency, damping, inertia or angular displacement of the stick. The aim of these studies was to optimize the ASSU's parameters according to the control law used in the helicopter.
2) *Development of Haptic cue functions*. The literature reports a large number of articles developing safety flight envelope and navigational aid functions ([4], [5], and [6]) These studies often focused on the model to calculate the critical parameter, and not on the type of haptic cue to provide to the pilot.
3) *Loop modeling: Pilot + HC + ASSU*. Other studies have focused on the modeling of the whole piloting loop, incorporating a helicopter flight mechanics model, a representation of the pilot behavior for a given task, and a model of an ASSU such as [7] and [8]. This approach allows to study the influence of the stick's parameters on the helicopter's flying qualities.

So far, to our knowledge, there is a lack of formal methods for defining haptic cues, other than simulator experimentation with pilots. 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) The modeling of a complete simulation loop to evaluate the haptic cues defined from these criteria.

It is expected that this approach will help the development and testing of haptic cues, by reducing the number of simulator trials. The following sections focus on the modeling of the piloting simulation loop, and in particular, the work done to develop a pilot activity model which takes into account haptic cues. The different criteria to allow the specification of these haptic cues will be addressed in future communications. Results obtained from an experiment, summarizing trends of the haptic detection of pilots are provided, as well as a detection model included in the activity pilot model.

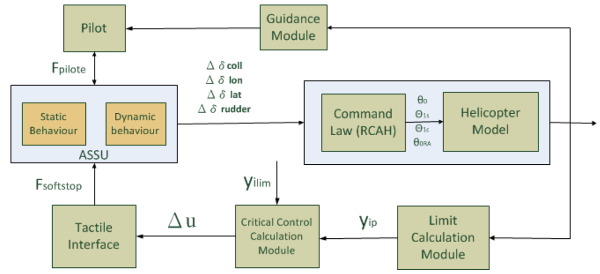

Fig. 2. Haptic feedback loop including an activity pilot and helicopter models.

II. CUEING PROTECTION FUNCTION

The first cueing function chosen for the modeling of the simulation loop was the limitation of bank angle to cue the pilot to limit the angle of inclination ϕ to a maximum of 30°. The helicopter model is "augmented" with a RCAH (Rate Command Attitude Hold) control law. Thus, the stick positions directly control the angular speeds. Automatic turn coordination (in order to cancel sideslip) has also been added.

III. SIMULATION LOOP

In order to represent the real dynamics of the complete system, each element has been integrated as a module in a SIMULINK model as schematized on Fig. 2. The helicopter model manages four control axes (roll, pitch, yaw, and collective) and several flight aids (ATT, SAS, Vx/Vz hold) can be selected, in addition to the RCAH law.

The model includes, in the feedback loop to the stick, a module (defined in [11]) which allows the computation of the parameter to be limited, and its conversion into flight command. Thus, equation (1) provides the maximum pilot command in roll $\delta \mathrm{DDL}_o$ before exceeding ϕ_{max},

$$\delta DDL_o = \sqrt{\frac{2c\Delta\phi}{\phi_{max}}} \tag{1}$$

where c is is the SS's return speed to neutral position, and $\Delta\phi$ the difference between ϕ_{max} and the current ϕ.

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.

A. Pilot Model

A precision pilot model, described by McRuer [10], has been integrated. It provides a list of some aspects of human behavior Y_p when controlling an element of an aircraft Y_c. This model adds the neuromuscular dynamics of the pilot to the well-known crossover model (2),

$$Y_p Y_c = \frac{\omega_c e^{-\tau s}}{s} \tag{2}$$

where Y_p and Y_c are the Pilot an Aircraft transfer functions, ω_c the crossover frequency, and τ the transport delay time caused by the pilot neuromuscular system.

B. HC Model

Non-linear rotorcraft modelling and simulation is provided by the full non-linear flight mechanics code Flightlab (developed by Advanced Rotorcraft Technology).

C. ASSU Model

The first objective of an active side-stick is to reproduce the behavior of "classical" sticks or yokes. A mass-spring-damper system is then generally accepted as a model of the ASSU. Therefore, the active stick can be modeled by a force-input position-output system of second order for each one of its axes (3):

$$\frac{x}{F_{pilot}} = \frac{1}{K}\frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n} \quad (3)$$

where $\omega_n/2\pi$ is the model frequency, K is the spring's stiffness of the system, and ξ is the damping.

Other elements have been also integrated in the simulation, such as a guidance module, which allows the transmission of pilot instructions in terms of flight parameters (for instance, hold an inclination angle or a forward speed). This module will be improved, enabling more complex piloting tasks.

IV. SENSIBILITY EXPERIMENT

In our study case, the classical approach for building a pilot model could be to measure the error between the current roll angle and the targeted one and to apply corrections (in terms of lateral stick position) to minimize this error. Delays, transfer functions, etc. could be added and adapted to fit to a realistic pilot behavior. This approach would be quite similar to classical and very well-known control methods. The goal being to be able to develop, ab initio, an haptic feedback, our pilot model has to "feel" the variation of the ASSU behavior due to the presence of haptic cues such as force gradients, SS, detent, etc. Moreover, it appeared several questions concerning the cue ability of pilots:

- How do ASSU and cue feedback parameters affect detection? What are their values?
- What is the probability that the pilot detect the cue feedback as a function of these parameters?
- What are the force thresholds [N] leading to the haptic feedback detection?

For this reason, an experiment was designed to analyze the detection of a cue feedback of type SS. It was chosen to test two populations: non-expert subjects and student pilots from the French Air Force Academy at Salon de Provence. The objective was not to compare the results obtained between these populations, but rather to allow the setting up of the experiment with non-pilot subjects and its improvement with more experienced subjects. As the subjects were not helicopter pilots, a simplified linear model was used for the lateral dynamics. The forward speed was kept constant while the vertical motion highly damped.

TABLE I

A SUMMARY TABLE WITH DAMPING AN FREQUENCY COMBINATIONS.

N° Set	Frequency [Hz]	Damping
1	3	0.5
2	5	0.5
3	3	0.75
4	5	0.75
5	3	1.25
6	5	1.25

TABLE II

A SUMMARY TABLE WITH VALUES OF QF, SPEED OF THE GREEP, AMPLITUDE AND POSITION OF SS.

Parameter	Value
QF	[0.5; 1; 1.25]$(N.\deg^{-1})$
Grip speed	[Slow; Fast]
Amplitude of SS	[3; 6; 9] (N)
SS Position	[± 3, ± 7; ± 10; ± 14] (deg)

This experiment took place in the prototyping and simulation environment PycsHel at Salon de Provence ONERA center, which enables real-time piloted simulation scenarios. The simulator has two ASSUs equipping the cyclic and collective controls of the pilot.

In the experiment, the subject had to sweep the grip alternatively between right and left positions, and pressed the trigger each time he felt a SS. In addition, a work task had been added forcing the subject to follow a target animated of a random movement along the vertical axis (to be followed with the collective stick). A total of 6 sets of SS combinations were tested in which the frequency or damping of the ASSU model is modified (Table I).

In each set, 3 levels of QF, 4 SS positions and 3 amplitudes were tried (Table II). Finally, we also asked the subjects to change the sweeping velocity between two conditions, namely "slow" and "fast" (both being self-appreciated).

A total of 6 pilots performed all the sets with a previously learning phase. Each one of the sets consists of 144 combinations of SS randomly distributed and repeated 3 times. Each subject started by a different set number. A pause took place at the end of each set, during which the subjects were asked to complete a questionnaire about their sensibility and detection based on the different parameters tested.

V. RESULTS

In order to develop a pilot model based on the detection of effort feedback, statistical analyzes were carried out on the results of the experiment. These analyzes provided:

- Trends about the detection during the modification of the ASSU or haptic feedback parameters, as well as,
- A multiple regression model of the force/displacement applied by the pilot on the stick at the time of detection of the SS, as a function of ASSU and haptic feedback parameters.

A. Exploratory statistical analysis

According to our research, there have been no scientific studies to understand the effects of ASSU's and haptic parameters on human detection. For this reason, an exploratory analysis of variance (ANOVA) of the mean detection per person and combination was carried out.

The analysis results and pilot's comments collected on the questionnaires are presented below:

1) No effect of the ASSU's model frequency was perceived on the SS detection. However, a correct combination of Frequency and Damping is necessary so as not to generate resonance oscillations on the grip. In fact, to the question *"Does this combination generates any oscillation at the starting point of the SS?"* most of the subjects affirmed to have felt them during the set 1 and especially in the set 2. Some others pointed out that felt vibrations all during the experiment in the rest of the sets, which is certainly due to a slight force ripple/cogging.
2) We found a significant effect of the interaction between the QF and the Amplitudes of the SS. The Fig. 3 shows mean detection for each amplitude of SS and QF tested. We observe how QF augmentation decrease the mean detection in particular for 9 N amplitude (respectively Mn 0.78, Mn 0.66, Mn 0.61), 6 N (respectively Mn. 0.61, Mn 0.55, Mn 0.45) and to a lesser extend 3 N (respectively Mn. 0.26, Mn. 0.22, Mn. 0.20). The subjects have been asked to rank and comment the different values of QF tried in the context of the detection and pilot task. Most of them (4/6) preferred the low-value QF and highlighted the ease to detect at QF 0.5, including the extremely-placed SS (close to the mechanical stop). Only one subject chose to rank first the QF 1.25, and the other admitted that *"I feel less [SoftStops] with a QF 1.25. [...] A QF 0.5 makes me to detect less near the neutral point because the grip becomes really sensitive. In the other cases, it helps to improve detection. [...] The best concession is, in my opinion, QF 1"*.
3) The ANOVA also signaled a significant effect of the interaction Damping-QF. In Fig. 4, we observe again how the increasing value of the QF drops the mean detection for the different damping factors. In the case of the damping, the low-value 0.5 implied better detections, excepting for the QF 0.5.
The student pilots noted their preference concerning the different sets tested. The set 4 (Damping 0.75 Frequency 5) resulted to be the best rated, the set 1, 2 and 3 were all rated equally, followed by the set 5 and finally the number 6. The last two were said to be tiring and difficult to allow SS detection. One of the military students commented: *"We tend to feel more SS in sets 1 and 2, because we had to exert less force on the grip and we remain sensitive to the variations of force"*. He also mentioned what seems to explain why the combination QF 0.5 - Damping 0.5 was less detected/ *"However these sets [1 and 2] do not allow, in my opinion, to fly a helicopter because the ASSU is too sensitive. With a QF 0.5, we often arrive at the mechanical stop without any effort"*.
4) Finally, two significant interactions of the piloting speed of the grip appeared on the ANOVA. The first one, QF-Speed interaction, revealed that the different QF combinations were differently affected by the ASSU's speed, which appears logical. The mean detection decreased of ΔMn 0.27, 0.22 and 0.18 for the QF values of 0.5, 1 and 1.25, respectively. In the second interaction, Position-Amplitude-Speed, appears that outward SS's positions (i.e. movements to the right) were slightly better detected and less affected by the piloting speed. Piloting speed also affected more to the positions close to the near point, and much less to positions -14/14 $^\circ$.

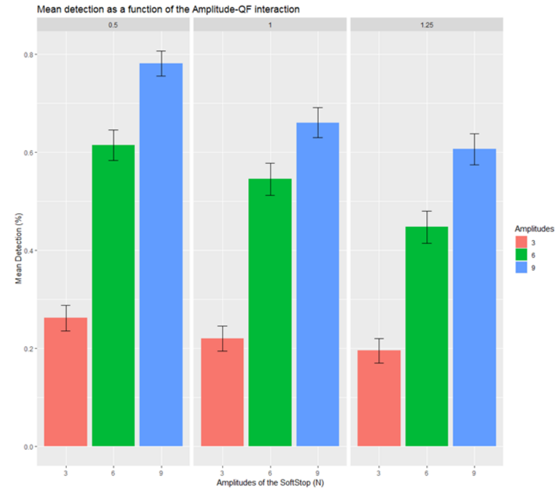

Fig. 3. Mean detection as a function of the Amplitude of the SoftStop and the gradient of the nominal force-displacement law (QF).

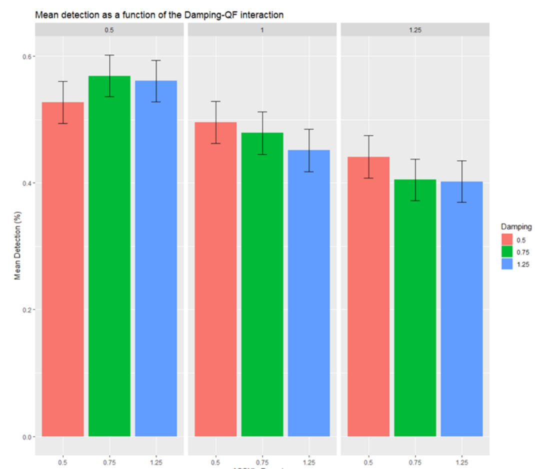

Fig. 4. Mean detection as a function of the ASSU's Damping and the gradient of the nominal force-displacement law (QF).

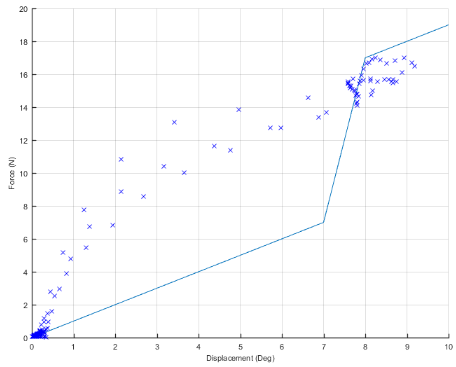

Fig. 5. Overshoot generated, in comparaison with the linear law, in response to a command with the ASSU.

TABLE III

A SUMMARY TABLE OF THE REGRESSION MODEL PREDICTING THE OVERTAKING SINCE THE SS'S POSITION .

	ΔR^2	B	SE B	β	P
Model δDDL	0.43				$<.001$
Constant		4.12	0.30		$<.001$
Damping		0.5	0.11	0.08	$<.001$
Amplitude		-0.53	0.04	-0.63	$<.001$
SS's Position		0.11	0.01	0.53	$<.001$
QF		-1.36	0.31	-0.22	$<.001$
Amplitude*QF		0.23	0.05	0.04	$<.001$

B. Regression Model

We performed a multiple linear regression 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.

So far no 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. On Fig. 5 we can observe how the response of the stick to a command differs from the linear static law. This dynamic behavior 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 SS. This undoubtedly affects haptic detection, since the pilots could detect the force gradient variation at different points, or even "fly over" the SS without noticing it. This behavior is not noticeable with the SAFRAN's ASSU, and future experiments led with this system should provide more repeatable and consistent results.

In parallel with this work, a regression model predicting the overtaking reached from the beginning point of the SS (ΔDDL) has been performed. This model explains 43% of the variability of the data obtained from the simulator (Table III[1]). Since the somatosensory system depends on a large number of factors (human physiology, experience, etc.), a probabilistic model of detection has been added (Table IV[1]).

TABLE IV

A SUMMARY TABLE OF THE REGRESSION MODEL PREDICTING THE PROBABILITY OF DETECTING A COMBINAISON.

	ΔR^2	B	SE B	β	P
Model Prob	0.31				$<.001$
Constant		0.18	0.04		$<.001$
QF		-0.09	0.04	-0.07	0.028
Amplitude		0.11	0.01	0.63	$<.001$
SS's Position		-0.002	0.00	-0.06	$<.001$
Speed		-0.26	0.04	-0.31	$<.001$
Amplitude*QF		-0.02	0.01	-0.02	$<.001$
Speed*QF		0.13	0.03	0.75	$<.001$
Amplitude*QF		-0.01	0.01	-0.31	$<.001$

TABLE V

MEAN FORCE TRENDS AS A FUNCTION OF AMPLITUDE AND POSITION OF SOFTSTOP AND FOR DAMPING, FREQUENCY, QF AND SPEED SET.

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

Despite a poor compliance with the measures, this model allowed us to set up the detection logic in the pilot activity model.

Alternatively, a simple model based on an interpolation of the mean force detection has been performed. This interpolation (Table V) shows some of the trends already mentioned,

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

As shown in Table V, providing mean force detection for a given set of ASSU's parameters (QF, Frequency and Damping), a multi-dimensional interpolation will be used for the other ASSU's parameters, and used as force detection thresholds in the pilot activity model.

VI. RESULTATS ANALYSIS

Based on the results obtained during the experiment, and with the objective of improving the detection of haptic cues, we could consider a nonlinear nominal law. In Fig. 6, the different parameters of the ASSU have been adapted according to the conclusions exposed above. Thus, the force nominal law, as a function of ASSU's displacement, and adapted as to improve pilot detection could be,

- The Nearest SS positions should be protected with larger amplitudes. On inward movements (pronotation), should be even larger since we are stronger.

[1] ΔR^2 explains the proportion of variance explained by the model, B, or b-values, are the estimates coefficients of the linear regression model, SE B are the associated standard error of the b-values, β are the standardized betas and P are the significance associated with the t-test for each b-value of our model.

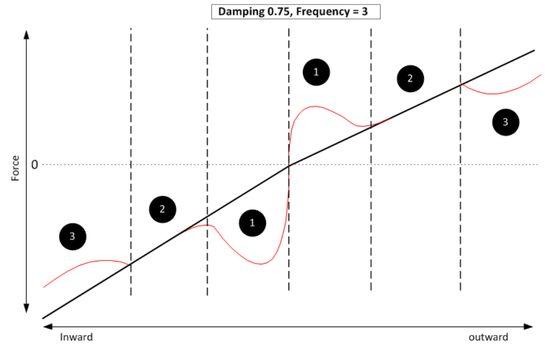

Fig. 6. The linear nominal law (in black) may be not optimally adapted to SS detection. A nominal law adapted (in red) depending on the SS position is here proposed.

- In the same way, the QF should be stronger on inward movements than on outward.
- Decrease of the QF near the SS position. This would reduce arm tension and improve detection.

Additionally, to make sure that pilots detect the haptic cue, the damping ratio could be increased when the pilot is operating near or in the SS. Due to the technical characteristics of the sticks used at Onera, this technic (proposed in [4]), could not be tested.

VII. Conclusions

A complete simulation loop is in development, which should allow the definition of haptic feedback laws for specific mission or piloting aid function. The definition of the haptic feedback should rely on criteria which remain to be defined, but which could be a composition of several ones such as the respect of critical parameter limitation, or some flight parameters, or the optimal task completion.

An experiment has been conducted in the PycsHel simulator to initiate the development of a pilot activity model able to detect the different force feedback generated by an ASSU. Statistical methods, adapted to the analysis of the ASSU's parameters, have been developed and could be used for the analyses of future experiments.

An analysis of the results obtained in simulator has highlighted the importance of adapting the different ASSU's parameters to facilitate the detection of haptic cues.

According to these results, it can be 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) *SS'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 fewer detections, 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 motion and which could reduce the SS detection.

VIII. Next Steps

The next steps will focus on the improvement of the pilot's detection models by means of the ASSU developed by SAFRAN E&D. Once the model of the activity of the pilot will have a representative response, depending on the haptic parameters and the requirements of the piloting task, the next steps to be done will be:

- The selection of an application case using the lateral cue feedback protection. These tasks should meet certain performance criteria and could be extracted from the ADS-33 standard specification, or from a piloting complex task.
- The integration of this task into the haptic loop simulation, and the optimization of the haptic feedback according to piloting and sensitive performance criteria that should be set up.
- The implementation of the selected case on the simulator, the analysis of the results and, if needed, the adaptation and improvement of the simulation loop.
- Ideally, the implementation of the same procedure for a haptic feedback law on the collective axis.

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