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# Development and Evaluation of Coupling Modes and Haptic Functions enabled by Active Inceptor in Cockpits

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## ABSTRACT

The potential uses of Active Side-Stick Units (ASSU) technology far exceed solely the case of fully programmable haptic feedbacks to one single pilot or the capability to generate haptic cueing for Flight Envelope Protection functions. Indeed, in dual pilot configurations, the capability to electronically link ASSU enables the coupling of the motions of the Pilot Flying (PF) and Pilot Monitoring (PM) controllers and opens potential new modes of communication between pilots, as well as between crew and Automatic Flight Control System (AFCS) when upper modes are engaged.

The EFAICTS (Ergonomic impact and new Functions induced by Active Inceptor integration in CockpiTS) project, started in December 2018, received funding from the Clean Sky 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation program under grant agreement No 820884. ONERA was the project coordinator and Safran Electronics & Defense the Topic Leader.

The EFAICTS project proposed to develop and integrate coupling and haptic functions for both Pilot/Co-pilot and Crew/Autopilot interactions along a Human-Centered Design approach, in which the end-users (i.e. pilots) were at the heart of the development, from the beginning of the project to the final evaluation phase.

The paper focuses on the flight scenarios definition; the PF/PM/AFCS interactions definition; the development of specific haptic feedbacks and ASSU coupling functions. All the concepts developed and assessed through modelling and intermediate tests were finally evaluated by experienced pilots on the ONERA simulation bench. The main results are presented in the paper.

## NOTATION

ACAH:	Attitude Command Attitude Hold
AFCS:	Automatic Flight Control System
AP:	Auto-Pilot
ASSU:	Active Side-Stick Unit / active inceptor
FEP:	Flight Envelope Protection function
IAS:	Indicated AirSpeed / upper AP mode
PF:	Pilot Flying
PFD:	Primary Flight Display
PM:	Pilot Monitoring
QF:	Linear force gradient of the force/displacement curve applied on the ASSU (QF=1 represents $1N/^{\circ}$ )
RCAH:	Rate Command Attitude Hold
TRC:	Translational Rate Command
VRC:	Vertical Rate Command

## INTRODUCTION

While on board systems are able to compile a high number of data and to feedback the result to the pilots, the principal

modes of communication remain visual cueing and audio alarms. However, thanks to Active Side-Stick Unit (ASSU) technology, haptic cueing can be an efficient and intuitive communication mode with the crew, when optimally configured. Therefore, the latest evolution of pilots' controllers, referred to as "active inceptors", provides static and dynamic tactile force (or haptic) feedback to the pilot at the grip:

- Haptic sense enabling different control operations without visual attention;
- Haptics providing new enhanced information channel if the feel is intuitive.

In addition, the potential uses of active inceptor technology far exceed solely the case of fully programmable haptic feedbacks to one single pilot. Indeed, in dual pilot configurations, the capability to electronically link active sticks enables the coupling of the motions of the left-seat and right-seat controllers and opens potential new modes of communication between the Pilot Flying (PF) and the Pilot Monitoring (PM) (Ref [1], [2], [3]). By contrast, cockpits equipped with decoupled sidestick controllers that do not provide active feedback have been highlighted in several aviation incidents or accidents such as described in [4]. Moreover, ASSU can also provide, to both pilot and co-pilot, back driven feedbacks based on the aircraft's Automatic Flight Control System (AFCS) actions, significantly improving the level of safety, making the actions of the automatic mode of control to the crew clearer

and allowing prompt recovery actions if needed. Some preliminary active inceptor requirements for a future tilt-rotor were proposed in [5], dealing with the maximal forces, requested bandwidth or signal noise. Dual pilot issues and inceptor failures were also partially considered but further analyses were carried out in this project.

Considering a new generation of active inceptors developed by Safran Electronics & Defense, the EFAICTS (Ergonomic impact and new Functions induced by Active Inceptor integration in Cockpit) project started in December 2018. This project has received funding from the Clean Sky 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation program under grant agreement No 820884, in which Safran Electronics & Defense is the Topic Leader and ONERA the project coordinator. The French flight test center, DGA-EV, was involved in this project as subcontractor.

The work proposed in EFAICTS addressed the benefits brought by active inceptors, in terms of safety, performance and situational awareness, through the:

- Development of optimized coupling functions and intuitive haptic functions for both Pilot/Co-pilot and Crew/Autopilot interactions,
- Validation of the functions through modelling and evaluations on a simulation bench.

EFAICTS project proposed a Human-Centered Design approach, in which the end-users (i.e. pilots) were at the heart of the development, from the beginning of the project to the final evaluation phase.

The paper will focused on the flight scenarios definition and evaluation; the PF/PM/AFCS interactions and transition phase definition; the development of haptic feedbacks and ASSU coupling functions and their evaluations. It will be shown to what extent the proposed solutions bring to situational awareness, safety and crew coordination improvement and their impact on pilots workload.

## FLIGHT SCENARIOS DEFINITION

EFAICTS project focused on a Civil Tilt-Rotor configuration, expected on-board systems (as detailed in [6]) and missions. If previous studies focused on the evaluation of coupling active-sticks in precise situations such as pilot training [1], the general framework of the missions considered in this project was civil air transport.

Thanks to a close cooperation with experienced pilots, ONERA established flight scenarios where a strong interaction is needed between pilots or between crew and AFCS. From an exhaustive list of flight phases (as shown in Table 3), a selection of scenarios has been done and tested through piloted simulations.

This selection process took into account the level of interaction during the flight phase combined to the criticality of the situation. This criticality was based on the probability of occurrence/frequency of the failure/task and the level of seriousness of the situation.

In order to select the most representative scenarios to be evaluated within the project, an approach has been proposed and followed.

Thus, an exhaustive list of flight phases has been drawn up. For each of them, potential issues encountered during these flight phases have also been listed. For example, during a take-off maneuver, the procedure is completed normally, or a loss of control occurs, or a rejected take-off has to be performed, etc. Then, for each of these combinations, two criteria were defined:

- The level of interaction between pilots during the phase
- The criticality of the flight phase

These criteria have been estimated thanks to several meetings with flight engineers and pilots of DGA-EV, leading to the computation of an index (comprised between 1 (not relevant) and 5 (very important)). This index helped us to determine the most pertinent flight phases to be studied in the framework of the EFAICTS project.

To compute the index, the criticality of each flight phase was ranked using the following table, depending on the probability of occurrence/frequency of the task, and the situation in terms of safety/workload/stress.

**Table 1. Criticality matrix**

Criticality: Probability of occurrence/frequency	Situation			
	Normal	N+	Problematic	Critical
Very low	E	D	D	C
Low	D	D	C	B
High	D	C	B	A
Very high	C	B	A	A

In addition, the level of interaction between crew for each flight phase was ranked, from very low to very high as shown in the following table:

**Table 2. Level of interaction matrix**

Level of interaction				
Very low E	Low D	Significant C	High B	Very high A

Table3 is showing the list of scenarios involving potential (or necessary) interactions between pilots.

Table 3. Complete PF/PM scenarios selection matrix

Id	Flight Phase	Scenario	Level of interaction	Proba./freq.	Situation	Criticality	Evaluation
1	Take-Off	Standard	Very low	Very high	Normal	C	2
2	Take-Off	Standard	Low	Very high	N+	B	3
3	Take-Off	LOC	Low	Very low	N+	D	2
4	Take-Off	LOC	High	Very low	Problematic	D	3
5	Take-Off	LOC	Very high	Very low	Critical	C	4
6	Take-Off	RTO	Low	Low	N+	D	2
7	Take-Off	RTO	High	Low	Problematic	C	3.5
8	Take-Off	RTO	Very high	Low	Critical	B	4.5
9	Take-Off	Collision avoidance	Low	Very low	N+	D	2
10	Take-Off	Collision avoidance	High	Very low	Problematic	D	3
11	Take-Off	Collision avoidance	Very high	Very low	Critical	C	4
12	Take-Off	Limit	Very low	High	Normal	D	1.5
13	Take-Off	Limit	Low	High	N+	C	2.5
14	Take-Off	Limit	High	High	Problematic	B	4
15	Cruise	Standard	Very low	Very high	Normal	C	2
16	Cruise	Standard	Low	Very high	N+	B	3
17	Cruise	AFCS disengagement	Very low	Low	Normal	D	1.5
18	Cruise	AFCS disengagement	Low	Low	N+	D	2
19	Cruise	AFCS disengagement	High	Low	Problematic	C	3.5
20	Cruise	Failure	Low	Low	N+	D	2
21	Cruise	Failure	High	Low	Problematic	C	3.5
22	Cruise	Failure	Very high	Low	Critical	B	4.5
23	Cruise	Limit	High	Low	Problematic	C	3.5
24	Cruise	Limit	Very high	Low	Critical	B	4.5
25	Approach (IFR)	Standard	Very low	Very high	Normal	C	2
26	Approach (IFR)	Standard	Low	Very high	N+	B	3
27	Approach (IFR)	Standard	High	High	Problematic	B	4
28	Approach (IFR)	Standard	Very high	Low	Critical	B	4.5
29	Approach (IFR)	Failure / limit	Low	Very low	N+	D	2
30	Approach (IFR)	Failure / limit	High	Very low	Problematic	D	3
32	Landing	Standard	Very low	Very high	Normal	C	2
33	Landing	Standard	Low	Very high	N+	B	3
34	Landing	LOC / Abort	Low	Low	N+	D	2
35	Landing	LOC / Abort	High	Low	Problematic	C	3.5
36	Landing	LOC / Abort	Very high	Low	Critical	B	4.5
37	Landing	Evitement collision	Low	Very low	N+	D	2
38	Landing	Evitement collision	High	Very low	Problematic	D	3
39	Landing	Evitement collision	Very high	Very low	Critical	C	4
40	Landing	Failure	Low	Low	N+	D	2
41	Landing	Failure	High	Low	Problematic	C	3.5
42	Landing	Failure	Very high	Low	Critical	B	4.5
43	Landing	Limit	Low	Very low	N+	D	2
44	Landing	Limit	High	Very low	Problematic	D	3
45	Landing	Limit	Very high	Very low	Critical	C	4

Table 4. Complete crew/AFCS scenarios selection matrix

Id	Flight Phase	Scenario	Level of interaction	Proba./freq.	Situation	Criticality	Evaluation
46	Take-Off	Standard	Very low	Very high	Normal	C	2
47	Take-Off	AFCS partial disengagement	Low	Low	N+	D	2
48	Take-Off	AFCS partial disengagement	High	Low	Problematic	C	3.5
49	Take-Off	AFCS partial disengagement	Very high	Low	Critical	B	4.5
50	Take-Off	AFCS total disengagement	Low	Very low	N+	D	2
51	Take-Off	AFCS total disengagement	High	Very low	Problematic	D	3
52	Take-Off	AFCS total disengagement	Very high	Very low	Critical	C	4
53	Cruise	Standard	Very low	Very high	Normal	C	2
54	Cruise	AFCS partial disengagement	Low	Low	N+	D	2
55	Cruise	AFCS partial disengagement	High	Low	Problematic	C	3.5
56	Cruise	AFCS partial disengagement	Very high	Low	Critical	B	4.5
57	Cruise	AFCS total disengagement	Low	Very low	N+	D	2
58	Cruise	AFCS total disengagement	High	Very low	Problematic	D	3
59	Cruise	AFCS total disengagement	Very high	Very low	Critical	C	4
60	Approach (IFR)	Standard	Very low	Very high	Normal	C	2
61	Approach (IFR)	AFCS partial disengagement	Low	Low	N+	D	2
62	Approach (IFR)	AFCS partial disengagement	High	Low	Problematic	C	3.5
63	Approach (IFR)	AFCS partial disengagement	Very high	Low	Critical	B	4.5
64	Approach (IFR)	AFCS total disengagement	Low	Very low	N+	D	2
65	Approach (IFR)	AFCS total disengagement	High	Very low	Problematic	D	3
66	Approach (IFR)	AFCS total disengagement	Very high	Very low	Critical	C	4
67	Landing	Standard	Very low	Very high	Normal	C	2
68	Landing	AFCS partial disengagement	Low	Low	N+	D	2
69	Landing	AFCS partial disengagement	High	Low	Problematic	C	3.5
70	Landing	AFCS partial disengagement	Very high	Low	Critical	B	4.5
71	Landing	AFCS total disengagement	Low	Very low	N+	D	2
72	Landing	AFCS total disengagement	High	Very low	Problematic	D	3
73	Landing	AFCS total disengagement	Very high	Very low	Critical	C	4

For examples:

- The frequency of a standard take-off, without any issue (case Id n°1, 2), is very high. In such a case, the situation can be considered as normal, or normal but needing a bit more attention (this situation is noted N+). These two situations lead to a criticality of C and B. In parallel, the levels of interaction between pilots are respectively very low, and low.
- The probability and frequency of a failure occurring during a landing is low (case Id n° 40, 41, 42). This could lead to three levels of situations depending on the failure: N+, problematic or even critical. This three situations lead to a criticality of D, C, B. In addition, the levels of interaction between pilots are respectively low, high and very high.

Taking into account the level of interaction and the criticality, a score (shown in the column “evaluation” of the tables) was computed by calculating the mean of these two criteria, for which 1 corresponds to normal/very low and 5 to Critical/very high. Ten flight cases were graded 4.5, but in order to limit the number of test scenarios to evaluate, a last selection was done among these candidates. So, two scenarios were finally selected to study the interaction between pilots:

- Scenario 1: Continuous Take-Off after one engine failure at Take-off Decision Point – ASSU Failure in flight,
- Scenario 2: Approach and landing / ASSU failure at Landing Decision Point.

The same approach was followed to define crew/AFCS scenarios, starting from the list of potential flight phases presented in Table 4.

The resulting selected scenarios for crew/AFCS interactions were:

- Scenario 3: Automatic take-off and AFCS disengagement (due to AFCS upper mode failure),
- Scenario 4: Cruise – AFCS disengagement (due to AFCS Upper mode failure).

Based on that first selection, the identified pertinent flight cases were then specified in details, leading to the definition of “Mission Task Elements”, as the objective was not to perform an entire mission/flight during the simulator trials, but to concentrate on the instant/situation/flight task where the interactions are high/necessary.

It was thus possible to precisely define and specify the scenarios that would be used all along the project for system/function developments, and that were carried out during the final evaluations. In particular:

- The flight phases / procedures (e.g.: Final approach and landing, autopilot disengagement, failures, etc.);
- The AFCS modes or advanced control laws engaged and potential transitions;
- The roles of the PM/PF/AFCS;

- The failures types and occurrences.

The four final scenarios that are presented hereafter, are representative of realistic situations, and share a common denominator in terms of pilots/system activities, interactions and potential issues. It has to be noted that, as this will be mentioned in the next chapter, the scenarios are all integrating some failures or “abnormal” situations for which a need of interaction at inceptor level is required or at least, expected. In classical, normal and standard flight cases or procedures, the interaction between pilots (at stick level) being very limited, or even inexistent.

Scenario 1:

Phase 1: The aircraft is initialized in Helicopter mode, Hover In Ground Effect, heading of 240° with a displayed radar altitude of 30 ft. PF translates to the Take-Off Point. Right turn to face the runway (314°).

Phase 2: PF switches flight control Law to RCAH (or ACAH) before take-off. PF initiates Take-Off.

Engine failure occurs after Take-off Decision Point at Indicated Airspeed of 50 kts – Height=50ft –At engine failure, regulation maintains nominal rotor RPM. PF continues Take-Off.

Phase 3: PF accelerates to 80kts and climbs at 1000ft/min. PF makes a left turn in climb to reach heading 270°. ASSU lateral axis failure at ALT=250ft. PF can continue to manage the flight or transfers authority to PM. The engine and ASSU failure occurrences can be modified during trials.

Functionalities/features evaluated:

- Haptic cueing dedicated to flight control laws,
- One engine failure warning through haptic function,
- ASSU failure warning through haptic function + force control logic,
- Coupling logics between pilot inceptors,
- Authority transfer logics / warning haptic function

Scenario 2:

Phase 1: The aircraft initialized in Helicopter mode at Indicated Airspeed of 80kt – Altitude=500ft, facing runway 134°.

Law engaged ACAH or RCAH. No AP mode engaged  
Phase 2: ASSU failure on longitudinal around Landing Decision Point: Height=50ft. PF continues landing. PF can continue to manage the flight or can transfer authority to PM.

Functionalities/features evaluated

- Coupling logics between pilot inceptors,
- ASSU failure warning through haptic function + force control logic,
- Authority transfer logics / warning haptic function,
- Glide slope Haptic Guidance Function

Scenario 3:

Phase 1: The aircraft is initialized in Helicopter mode, Hover In Ground Effect, facing runway 314° with a displayed radar

altitude of 30ft. PF engages TRANSITION UP mode from ACAH or RCAH (VRC on vertical axis)

Phase 2: AFCS malfunction (IAS upper mode) at Indicated Airspeed of 60kt – Height=200ft. Amber (warning) light appears during 5 seconds (duration could be changed) on the defected mode. After this warning, AP mode is disengaged. AFCS is still controlling the other axes. PF continues Take-Off

Functionalities/features evaluated

- ASSU back-drive logics (AFCS controlling ASSU motions),
- Authority transfer logics / warning haptic function,
- AFCS Failure warning through haptic function,
- Coupling logics at stick level

Scenario 4:

Phase 1: The aircraft is initialized in AC mode, level flight at IAS=150kts, HDG 90°, Altitude=3000ft. PF engages IAS, ALT.A or VS, HDG modes – RCAH/VRC back-up laws  
PF enters variations from 90° to 240° in HDG

PF enters altitude variations in ALT.A (from 3000ft to 5000ft)

Phase 2: AFCS Failure at ALT=3200 ft - HDG or ALT.A modes disengaged.

AFCS transfers authority to crew (PF) on the defected axis.

Visual Meteorological Conditions and Instrument Meteorological Conditions were tested.

Compared to Scenario 3, potential longer transition phase due to a lack of attention (3s instead of 1s in scenario 3)

Functionalities/features evaluated

- Back-drive logics,
- Authority transfer logics / warning haptic function,
- AFCS Failure warning through haptic function,
- Coupling logics

## DEFINITION OF PILOT/COPILOT AND CREW/AFCS INTERACTIONS

The following aspects have been studied in the project, and are addressed in the paper:

- Coupling strategies and logics between sticks and flight control system
- Conflict/authority management and take-over/disengagement logics;
- Transition phases;

Regarding the last aspect, transition phases between “hands-off” and “hands-on” situations have been analyzed as well as the authority transfer in between pilots and between pilots and the flight control system. Failure cases of the AFCS or at inceptor level were also considered as this implies a possible reconfiguration of the coupling modes and of the authority.

A brief reminder:

In aviation, the first officer is the second pilot (also referred to as the co-pilot) of an aircraft. The first officer is second-in-command of the aircraft to the captain, who is the legal

commander. In the event of incapacitation of the captain, the first officer will assume command of the aircraft. Control of the aircraft is normally shared equally between the first officer and the captain, with one pilot normally designated the "Pilot Flying" and the other the "pilot not flying", or "Pilot Monitoring", for each flight. Even when the first officer is the flying pilot, the captain remains ultimately responsible for the aircraft, its passengers, and the crew. In typical day-to-day operations, the essential job tasks remain fairly equal.

Traditionally, the first officer sits on the right-hand side of a fixed-wing aircraft ("right seat") and the left-hand side of a helicopter.

### Definition of PF/PM interactions

Let's start first with general considerations: during "normal" flight situations, interactions at sticks level between PF and PM are very limited, even non-existent. PM is not close to commands and it's only when the situation becomes more stressful/dangerous or critical (due to a failure/malfunction, bad external conditions or if the pilot is performing wrong actions) that the PM is getting closer to the commands, to be able to take-over if necessary.

In addition, PF generally engages AP modes at the beginning of the flight and uses them all along until landing, especially on commercial flights.

The roles of the pilot and co-pilot are generally “always” the same:

- Pilot on command (PF) keeps controls.
- PM assists PF (reading parameters, managing overall flight, etc.)

Nevertheless the transfer of controls is possible, if the PF is “unable” to perform the piloting task, or if the Standard Operation Procedures impose such a transfer in the corresponding circumstances.

### Coupling strategies and logics between pilot and co-pilot sticks

In the coupled active inceptors, the force deflection characteristics of a mechanical linkage can be emulated through the ability of the system to provide synthetic mass-spring-damper feel in real time manner. The inceptor coupling is achieved by allocating dedicated electrical links to transmit the forces of one sidestick to the other. Thus, the behavior of the inceptors on the pilot flying's (PF) control station can be replicated on the inceptors of the pilot monitoring (PM) through the electronic coupling of the active inceptor system. The goal being to emulate a mechanical linkage between inceptors.

But active side-stick technology offers the capability to create different coupling logics at inceptor's level. The following ones were implemented and evaluated:

#### Decoupled mode:

The sticks are not linked. They can have different/independent motions and there's no interaction between them.

It has to be mentioned that the decoupled mode will be available on the simulator but its study is out of the scope of the EFAICTS project.

Based on the ones used in Airbus airliners, the rules/logics to be applied in this particular mode are presented hereafter but won't be discussed or analyzed within the project. Nevertheless, the possibility to switch to this mode was available.

#### **Master/slave coupling mode:**

The sticks are linked. The slave stick follows the master's motions and can't interact. It's a "one way" interaction, from master to slave. The master stick imposes its motions to the slave. Slave feels being linked as with a mechanical linkage with the master stick, with a very high stiffness. Master has no force feedbacks from the slave stick.

#### **DUAL mode:**

The sticks are linked. This linkage emulates a mechanical linkage between sticks with a very high stiffness.

In such a way, sticks have identical motions. The interactions are mutual, the motions of a stick being felt on the other.

It strives to emulate the classical coupling between mechanically linked controls.

Nevertheless, contrary to a real mechanical linkage between inceptors, it is possible to decouple when the pilots apply opposite force leading to a fight force. An automatic decoupling due to force fight was tested, with a force threshold of 25N.

In DUAL mode, the coupling ensures identical forces transmission, and thus identical motions of the primary and the secondary stick (as a mechanical linkage), but it is also possible that the forces transmitted between sticks are not equal, leading to different inceptors displacements. Three different modes, called "asymmetrical", have been tested:

##### **"Asymmetrical min":**

The sticks are linked and this linkage emulates a mechanical linkage as long as the force applied is lower than 5N. For forces above 5N, the transmitted force (and thus, position) is saturated to 5N (corresponding to a position of 5° with a QF=1).

This saturation is applied on both stick (pilot and copilot). There's a limited mutual interaction between sticks, a limited/saturated force can be felt coming from the other stick.

The idea was to allow only small interactions between inceptors, for limited trajectory corrections for example.

##### **"Asymmetrical max":**

In this mode, only forces above 5N are transmitted. If one inceptor is moved due to a force lower than 5N, the other inceptor is not impacted, and thus, doesn't move. As soon as the force applied is higher than 5N, the force is transferred.

Here, the logic enables to avoid small unintentional inputs to be felt by the other pilot, while larger inputs (expected to be intentional) are transferred.

##### **"Asymmetrical half":**

In this mode, it is necessary to designate a primary pilot. The total force of the primary pilot (or PF) stick is transmitted to the PM stick, while only half of the force from PM is transferred to PF inceptor. In this mode, PM stick motions are the same than PF ones, while PF stick motions are half of the PM stick motions.

This logic is close to the Master/slave mode, but the slave is able here to interact with the master pilot, by producing a limited amount of forces.

These "asymmetrical" coupling modes were evaluated and results are discussed further in the paper.

#### **Authority concerns:**

In Master/slave mode, it is necessary to designate a primary pilot to the FCS. Thus, the master is always the Pilot Flying.

In DUAL mode, as the inceptors are linked and can interact, several possibilities are offered:

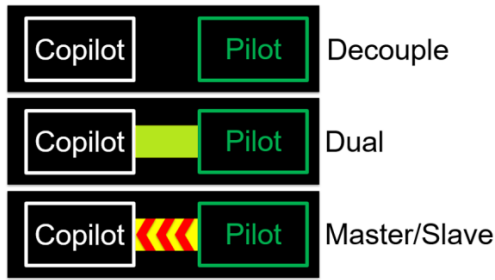
- The controls can be taken from only one stick, as the emulated mechanical linkage implies, and imposes, identical positions to both sticks.
- Mean of the two pilots sticks: the stick positions being almost the same (linkage as a mechanical linkage)
- Weighting/coefficients applied on the position differences between sticks: a priority pilot would have to be defined – This solution was considered **complex and with no interest** and was not implemented.
- Commands from the last "request": but even if a dedicated light/indicator explicitly is showing the pilot in command is present on the PFD, **this might be confusing**.

It has been stated that in dual mode, the need of designating a primary pilot is useless as the sticks are linked and any pilot can have control. "Authority" can be stated aurally, as it is done up to now. Thus, from the FCS "point of view", it is not necessary to define a primary inceptor/pilot. Controls sent to FCS can come from one inceptor, any of them, or based on the arithmetic mean of both inceptor positions (solution used in our system).

In the framework of the EFAICTS project, authority is given to the designated primary pilot (pilot "on command") in decoupled mode. The Airbus airliners logic was implemented but not tested or evaluated, since it flies since decades.

A specific indicator was implemented on the Primary Flight Displays where the designated primary pilot is highlighted in green as shown in Figure 1, as well as the coupling mode engaged.





**Figure 1: Light indicator showing primary pilot (“pilot on command”) + coupling mode engaged**

#### Switching logics and associated authority logics

**Table 5: Switching Logics**

Mode transition	1		2		3		4		5		6		7	
	Coupling mode		Coupling mode		Coupling mode		Coupling mode		Coupling mode		Coupling mode		Coupling mode	
Action from:	Pil	Copil	Pil	Copil	Pil	Copil	Pil	Copil	Pil	Copil	Pil	Copil	Pil	Copil
Pil	Decoupled		Decoupled		Decoupled		DUAL	DUAL	DUAL	DUAL	Decoupled		DUAL	DUAL
Pil	Master	Slave	Master	Slave	Master	Slave	Master	Slave	Master	Slave	Master	Slave	Primary	Slave
Pil	Primary		Primary		Primary		Primary		Primary		Primary		Primary	
CoPil	Slave	Master	Slave	Master	Slave	Master	Slave	Master	Slave	Master	Slave	Master	DUAL	DUAL
CoPil	Decoupled		Decoupled		DUAL		DUAL		Slave	Master	DUAL		Slave	Master
Pil	Master	Slave	Master	Slave	Master	Slave	Master	Slave	DUAL	DUAL	Master	Slave	DUAL	DUAL
CoPil	Primary		Primary		Primary		Primary		Primary		Primary		Primary	
Pil	DUAL	DUAL	Slave	Master	Slave	Master	Slave	Master	Slave	Master	DUAL	DUAL	DUAL	DUAL
Pil	Slave	Master	Slave	Master	Slave	Master	Slave	Master	Slave	Master	Slave	Master	Slave	Slave
Pil	DUAL	DUAL	Decoupled		DUAL	DUAL	DUAL	DUAL	Master	Slave	DUAL	DUAL	Master	Slave
Pil	Slave	Master	Master	Slave	Decoupled		Master	Slave	Master	Slave	Decoupled		Master	Slave
CoPil	Decoupled		Slave	Master	Slave	Master	Slave	Master	DUAL	DUAL	DUAL	DUAL	DUAL	DUAL
		Primary		Primary		Primary		Primary		Primary		Primary		Primary

A first analysis and exchanges with pilots led to the conclusion that this logic is too complex and confusing.

Couplings were therefore managed differently all along the project:

- Coupling modes are selected through a control panel on the Secondary Flight Display (easily reachable by both pilots) and clearly identifiable when it is not automatically managed (e.g. ASSU failure or force fight automatic decoupling function) as shown in Figure 2:



**Figure 2. Coupling modes selectable on Secondary Flight Display.**

- Authority is set through a “take-over” push-button
- Decoupled mode: Through its selection on control panel, force fight function (that automatically decouples the sticks), or in case of ASSU failure when the functional inceptor requests the transfer of authority.

#### Inceptor failure case

Safran’s inceptor internal architecture is based on direct-drive motors, with no gearing, mitigating (and even preventing) the possibility of stick jamming. In addition, as the system is featuring quadruplex displacement sensors, the probability of a total motors loss is highly improbable. The

Different switching logics can be applied to switch between the coupling modes previously defined.

Hereafter, seven different switching logics were proposed, based on the hypothesis that the status is changed through a push-button on inceptors.

Starting from a decoupled or dual mode, the column “Action from” represents an action on “a takeover/request button” from the pilot or the co-pilot.

The resulting coupling mode is proposed as well as the associated authority status:

only impact could be a reduce level of maximum reachable force feedback. Nevertheless, due to aircraft manufacturer and certification requirements, a back-up mode will be introduced, which could be activated for the worst failure case: In back-up piloting mode, the stick is locked in position thanks to brake devices and pilot controls the aircraft by applying forces on the stick. Pilot intentions are then collected by force sensors inside the grip.

This feature (at least an emulation of it) was implemented on inceptors available at ONERA. As the brake device was not available yet on our inceptors, the lock has been reproduced by applying a high force gradient (30N/°) preventing stick motions (or very slight ones).

This type of failure and the strategy to keep control has been evaluated by piloted trials, to assess if the transients, due to a shift from position to force control are acceptable, and if the developed force control laws enable the continuation of the flight. The coupling between inceptor in this case was also evaluated.

#### Inceptor failure during “hands-on” operations

The only ASSU failure considered in this project was the worst one, corresponding to the (controlled) lock of the inceptor at its current position and the shift from position control to force control.

In this situation, the lock is simultaneously applied on all axis of the failed ASSU:

- Coupling considerations:



AFCS back-drive of the failed inceptor is no longer possible

Master/slave mode is possible if the master is the failed inceptor. If transfer of authority is requested from failed to functional inceptor, an automatic switch to decoupled mode is performed.

DUAL mode is no more possible.

Decoupled mode is of course possible

- **Authority considerations:**

While authority could be automatically OR manually managed to the operational inceptor, since the failed ASSU is still capable of sending controls to FCS through force sensors, no automatic transfer is recommended (as the secondary pilot might not be in position to take control)

In addition, it is assumed that collective and cyclic are always in the same coupling mode

### **Inceptor failure during “hands-off” operations – AP back-drive**

Auto-pilot back-drives all inceptors but a failed inceptor/axis can't be back-driven. Therefore, the failed inceptor, locked in position, is no more back-driven (but all others are).

### **Definition of crew/AFCS interactions**

#### General considerations:

When upper AP modes are engaged, interactions between crew and AFCS at sticks level depend on the flight case.

During take-off and landing, PF is close to commands, even hands-on, ready to take control. The reaction delay considered is 1 second.

In cruise, PF is much farther from sticks, leading to very limited interactions. The reaction delay considered here is 3 seconds.

A transfer of authority from AFCS to PF is thus only needed when a failure occurs on an AP mode (or of course when PF wants to take control back)

In helicopters, flight controls are already back-driven by the trim actuators and classical mechanical links.

In Airbus airliners, the side-sticks are not coupled and when upper AP modes are engaged, they remain fixed to the neutral position.

Different possibilities were tested:

- No back-drive of the inceptors by AFCS
- AFCS back-driving all inceptors, both PM's and PF's
- AFCS back-driving only PF's inceptors

The different back drive logics developed and tested will be detailed in the next chapters.

### **Conflict/authority management and take-over/disengagement logics**

It is worth mentioning that most modern helicopter flight assistance functions, beyond stability augmentation, detect pilot actions. Pilot follow up functions are called “hands on/feet on” functions, “fly through”, “transparency” or “override” modes. Upon detecting pilot action, the AFCS interrupts its long-term hold function to momentarily replace

it by pilot inputs. In the framework of the project, “fly through” modes were developed and implemented but were not used (neither tested) during scenarios evaluations, as already available and frequently used in modern machines.

A set of general rules has been identified for the management of the authority on the inceptors:

- If the coupling mode between inceptor is set to Master/Slave or Decoupled, one inceptor shall be used as a primary (priority) input for the flight control computer in case of AP disengagement, or if a “fly through” function is available.
- The primary inceptor shall be designated by a light on the respective inceptor or on the PFD;
- Either pilot shall be able to assume primary input with a “takeover button”;
- If a force control law is available (enabling piloting through an iso-static inceptor), it is possible to change over to a set of inceptors whose force-feel system has failed.

In the case of an AP disengagement from AFCS:

- Automatic disengagement from AFCS and transfer of the controls to the priority pilot (PF) ,
- No need of PF approval: automatic transfer.

In the case of an AP disengagement required by crew, different solutions are possible:

- Based on force threshold (Force sensor required – hands-off = no force measured) – only in case of no “fly through” function available.
- Press a button to disengage the AP

The use of a button is preferred: this solution is already applied in helicopters; other solutions may lead to unintentional AFCS disengagement due to unintentional inputs on flight controls.

During AFCS back-drive, the coupling modes at inceptor's level can be automatically set to any of the coupling modes, but it was set to DUAL in order to follow the pilots' preferences.

### **Transition phases and associated fading functions in case of inceptors/AP commands desynchronization**

This question is dealing with the transitions phases between “hands-off” and “hands-on”, and more specifically with the transition between automatic flight phases and recovery from pilots.

In case of AP disengagement, the impact depends on the situation:

- Pilot is hands-off, the inceptor position is supposed to be back driven at the “good” position: no impact
- Pilot is hands-on and acting on the inceptor: the inceptor position may be different than the required one and fading function recommended to avoid discontinuities in commands sent to FCS.

So, if there's no “fly through” function:

1. Pilot can interact, change inceptor position but no command sent to FCS;  
The force gradient (also called QF=Q Feel) remains at the nominal value (1N/°);
- or
2. Pilot can't interact, i.e. can't change inceptor position;  
QF increased to avoid any displacement (QF=20N/°);

In the second solution, in case of AP disengagement, the inceptor position is supposed to be back driven at the “good” position but the QF has to be immediately changed to the nominal value of 1N/°.

The second option was preferred by pilots. The possibility to move the stick without any action on the FCS could be confusing.

Remarks:

If “fly through” modes are not implemented, inceptor position changes (due to pilot) are not taken into account by the AFCS. In case of AP modes disengagement, if the pilot is acting on the inceptor at the same moment, this could lead to a desynchronization/discrepancy of the commands sent to FCS resulting in a transient (and potentially adverse) behavior of the aircraft attitudes.

In this case, fading functions should ensure a smooth transition between the commands sent to the FCS.

## HAPTIC FEEDBACKS AND COUPLING LOGICS

The analysis of these modes of interaction led to the specification and the development of different coupling logics and haptic feedbacks/cueing functions for many different goals. Indeed, specific haptic cues can be used for a better understanding and management of:

- The conventional or advanced control laws (RCAH, ACAH, TRC, ACVH, VRC),
- The coupling between pilots inceptors,
- ASSU back-driven by the AFCS,
- The authority transfer between pilots and between pilot and AFCS,
- Flight Envelope Protection functions (FEP),
- Failures of aircraft components, AFCS or ASSU.

Specific haptic cues were implemented and tested to evaluate their benefits when using advanced control laws (RCAH, ACAH, TRC, VRC),

- Control law transitions warning through vibrations (cyclic / collective) :  
In order to warn pilot of a transition between active control laws (done by pilots or automatically by the FCS) and in addition to the PFD lights, a specific haptic function has been integrated based on vibrations on cyclic (change between SAS, ACAH, RCAH, TRC laws) and collective (VRC control law change).
- Detents on cyclic and collectives:

Detents on the neutral position of the collective and cyclic were implemented, enabling the recognition of the level flight (on collective), null rate command or attitudes depending on the law engaged (RCAH or ACAH), or null velocity in TRC.

- Friction on TRC:  
When TRC is engaged, friction of 2N on the cyclic longitudinal axis was set instead of the classical force/displacement (1N/°) law.
- Trim release function/beep trim:  
In RCAH the possibility to trim the inceptor in another position than 0 is not recommended, as this implies pitch or roll rates. This is also true for beep-trim function.

Haptic cues were also design for coupling mode changes:

- In order to inform both pilot and co-pilot that a coupling mode change has been requested (e.g. DUAL <=> master/slave modes), and in addition to the dedicated PFD symbology, a specific haptic function has been integrated based on vibrations on the cyclic.

For the cases where the ASSU back-driven by the AFCS:

- Different logics: No Back-drive, Back-drive based on FCS commands, Back-drive based on augmented flight control laws.

If no back-drive, the sticks remain fixed.

If back-drive based on FCS commands, the stick motions are based on controls sent by AFCS to rotors/aerodynamic surfaces.

If back-drive based on augmented flight control laws, the inceptor's position is assumed to reflect the control position which would lead to the current objectives for the active control law. For example, in ACAH law, when the pilot is acting on the controls, the inceptor positions command target attitudes to be followed by the ACAH law. In the back driven mode, the tilt-rotor's attitudes resulting from the AP mode engaged are converted into inceptor's positions, corresponding to the ones which would lead to the current attitudes.

The back drive logic generates stick positions compliant to the controls to apply with the control law (in back-ground), or corresponding to the FCS “direct” commands. This is done by modifying the inceptor trim position (corresponding to a null force on the inceptor's force/displacement curve) at the required position.

Inceptor position changes (due to pilot actions) are not taken into account by the AFCS.

The force gradient (QF) of the force/displacement curves applied on the inceptors:

- may remain the same as in hands-on control (if “fly through” function available) or,
- can be increased to prevent any control interference from the pilot.

In the first case, the nominal force gradient is set to 2N/° (instead of 1N/°). The pilot is able to counteract the force applied to the inceptor and change the inceptor position (but with no effect). In the second case, the force gradient is

increased to 20N/°. The pilot is unable to change the inceptor position (or very slightly and temporally).

Haptic cues were also design in the case of authority transfer between pilots and between pilot and AFCS,

- Between pilots: a push-button is dedicated to transfer of authority + vibrations.  
Authority is **TAKEN**, not given.  
In order to inform both pilot and co-pilot of a transfer of authority between them, in addition to the dedicated PFD symbology, a specific haptic function has been integrated based on vibrations on the longitudinal cyclic, which is the inceptor on which the authority transfer button is.
- Between AFCS and crew: warning light + vibrations  
AP mode can be engaged or disengaged through push-button on PFD by crew.  
AP mode can be disengaged automatically by AFCS in case of failure  
Vibrations are generated at AP mode engagement and/or disengagement

Some Flight Envelope Protection functions (FEP) have been implemented through haptic feedback:

- Glide slope following  
A detent is positioned at the vertical velocity corresponding to a glide slope of  $-3^\circ$  (standard approach), replacing the one placed at the neutral stick position.
- Corridor limits/VNE:  
This function generates haptic cues on the longitudinal cyclic to warn the pilot that the aircraft is approaching a maximum predefined forward speed corresponding to the tilt-rotor corridor limit. Different cues were implemented and tested.  
Different types of vibrations: continuous or function of the IAS.  
“Negative” QF increase with IAS, limiting the forward stick motions.  
Stick trim position moving rearward, to decrease the speed.

In case of failures of aircraft components (AFCS, ASSU, or engines), the following haptic cues have been implemented and evaluated:

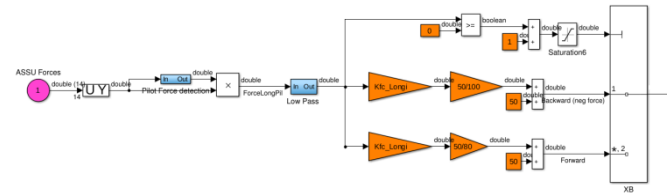
- One engine failure: 3 pulses of vibrations warning on the collective
- AFCS failure: 3 pulses of vibrations warning on the stick axis that will be disengaged
- ASSU failure: 3 pulses of vibrations warning at ASSU failure and automatic switch to a force control based law.

Force control laws were developed and implemented (requiring a force sensor on the grip), dependent on the flight control law and corresponding to the pilot actions on the stick.

In normal situation and when fully operational, based on the force/displacement curve (static behavior) and the predefined second order dynamics, the inceptor reach the position corresponding to the force applied by the pilot. These inceptor positions are then sent to the FCS.

If failed, the objective is then to generate pseudo inceptor positions, based on a force control law, to be sent to the FCS while the inceptor remain locked in position.

Thus, a proportional force control law was developed, in which the generated pseudo positions are proportional to the forces applied. In Figure 3, the proportional force control law Simulink blocs on the longitudinal cyclic axis are presented.



**Figure 3: Proportional force control law**

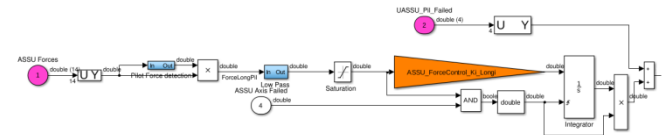
This force control law is very similar to the normal position based control law. For examples:

In RCAH, if the force is released, the pseudo position is null, the angular speeds are null, attitudes are hold.

In ACAH, a force has to be continuously applied to generate a pseudo inceptor position, and to maintain attitudes.

In the second case, it was considered that applying a constant force (to maintain constant attitudes) could be difficult and/or tiring. Thus, a second force control law was developed and is shown in Figure 4.

An integrator was added, allowing to release the force while continuing to generate a pseudo inceptor position.



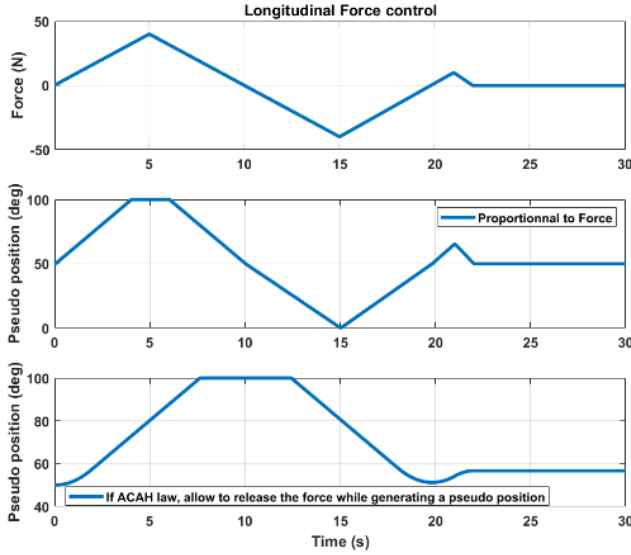
**Figure 4: “Integrator” force control law**

In the following Figure 5 and Figure 6, the pseudo positions corresponding to a same force application (first upper plot) are presented, for the proportional law (middle plot), and the “integrator” law (lower plot). In order to take into account ergonomic considerations, the longitudinal forward and rearward laws are slightly different, as well as the right and left lateral axis. The position (in %) sent to the FCS are saturated to 0 and 100% (50% corresponding to neutral inceptor position).

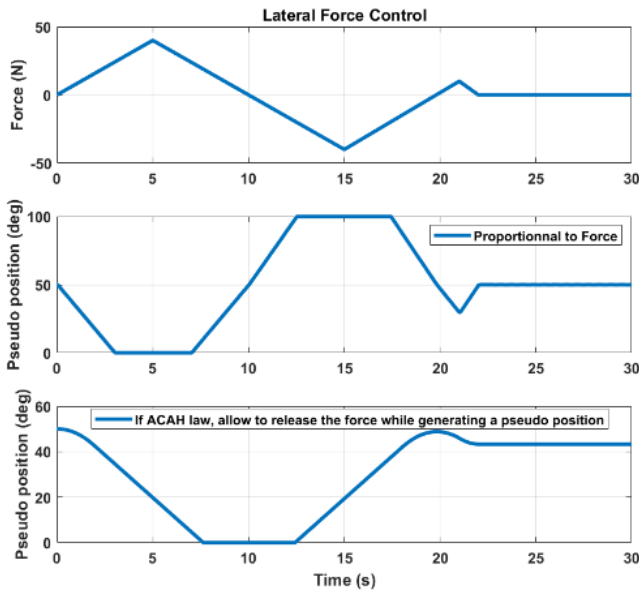
It can be seen that the proportional law (when not saturated) follows the force variations.

Regarding the “integrator” law, on the longitudinal axis for example, when the force is higher than 0N after 20s, the pseudo position increases from 50% to 56%, and remains constant once force is released. This allows to send 6% of

position controls without the need to apply the corresponding force on the stick.



**Figure 5: Pseudo inceptor positions on longitudinal cyclic axis**



**Figure 6: Pseudo inceptor positions on lateral cyclic axis**

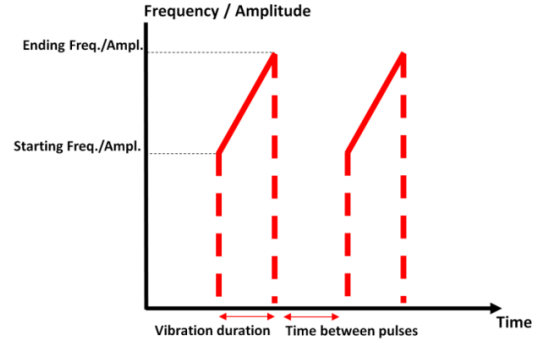
It has to be noted that, if the “integrator” law is potentially more ergonomic in the sense that it doesn’t require constant force applied on the stick in ACAH, this law should not be used associated with a RCAH flight control law, as rate commands could be produced while no force is applied.

In addition, when the FCS switches for position to force control at the ASSU failure detection, vibrations are generated on remaining functional inceptor.

A distinction has been made on the vibrations cues depending on their function through the number of pulses, respecting the following logic:

- 1 vibration for status change (AP mode engagement/disengagement, flight control laws, coupling change, etc)
- 2 pulses of vibrations for authority transfer
- 3 pulses of vibrations for any failure: 3 pulses, on the same logic when pilot says “failure, failure, failure”.

The following parameters defining a vibration could be adapted and modified during the trials



**Figure 7: Settable vibration parameters**

In most of the cases, the following parameters were set to the following values:

Frequency = 50Hz - Amplitude = 4N,

If one pulse, 1s duration,

If more, 0.2s duration, 0.2s between each pulse,

Constant amplitudes and frequencies were applied.

As different haptic cues could be generated on the same inceptor axis, prioritization logics were implemented. Thus, priority is given with the following logic:

1. Failure warning cues
2. Authority transfer between pilots
3. Status change (flight control laws, Auto-Pilot mode, coupling mode, etc.)

## EVALUATIONS THROUGH PILOTED SIMULATIONS AND RESULTS

All evaluations were performed in the PycsHel simulator at ONERA Salon de Provence (Figure 8).



**Figure 8: PycsHel simulator at ONERA**

This simulator and all integrated systems were detailed in [5]. It offers a dual pilot configuration, integrating 4 active side-sticks, 2 for cyclics and 2 for collectives (Safran's inceptors).

The Primary and secondary Flight Displays are based on tactile screens, not representative of existing machines, but providing the minimal information to the crew to achieve the flight tasks. All flight scenarios were "flown" over Marseille airport terrain database.

Each scenario required between 2 to 4 hours. This time being divided between the introduction (where each subject was given a briefing prior to starting the trial), the familiarization phase (in which pilots could become familiar with the simulator, controls, advanced control laws and displays), the scenario evaluation (composed of several test runs in which the pilots had to performed the flight task and an evaluation after each test run where pilots had to answer different questionnaires or miscellaneous questions).

The objective was to perform the evaluation in the condition of a dual pilot configuration, civil transport flight. Nevertheless, due to the different backgrounds of the pilots, discussions and feedbacks extended to other situations such as combat, search and rescue or instruction flights, tandem cockpit configurations or fixed-wing airliners or fighters problematics.

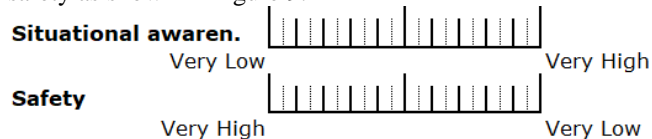
The results presented in this paper are based on a total 11 simulator trials, corresponding to around 40 hours. 7 pilots were involved in the evaluations presented in this paper, all very experienced, with an average number of flight hours of 3600. (Minimum 1500h, maximum 5300h).

6 of them were helicopter pilots from DGA-EV, with a large experience on many different types of helicopter and all having more than 2600 flight hours. One airline company pilot (flying on Airbus A320-A321) also participated to scenario 3 evaluation.

Six pilots tested the scenario 1, two pilots the scenario 2, five pilots the scenario 3 and two pilots the scenario 4. However, evaluations are planned to continue up to mid of May in order to collect the greatest number of results.

All subjects were asked to answer to questionnaires, remaining the main method of capturing the subjects' responses and opinions.

It was preliminary envisaged to use SART and NASA-TLX questionnaires during the evaluations but it appeared that these questionnaires were too detailed and relatively too complex compared to the evaluated functions and tests cases. Thus, it was preferred to directly ask the pilots to rate the situational awareness provided by a function from 0 (very low) to 10 (very high). The same rating was asked for safety as shown in Figure 9.



**Figure 9. Situational awareness and safety direct ratings.**

In order to answer these ratings, the following questions were asked for situational awareness: "How much situational awareness did you have?", "Did you have a good perception of the information about the machine and the environment; a good understanding of these information, allowing the anticipation of their evolution over time?". The question for safety was: "How safe did you feel, what was the level of safety during the task?"

Nevertheless, some specific functions were rated through the "Van Der Laan" pilot acceptance questionnaire. This questionnaire was developed by van der Laan, Heino and de Waard in order to define a standard way to measure operators' acceptance of new information technology. This scale assesses system acceptance on two dimensions, a Usefulness scale and an affective Satisfying scale [7].

In order to focus and analyze the benefits, acceptance or simply the pilot's point of view on some very specific features/functions/logics that were tested during the trials, miscellaneous questions were also asked to the subjects during the test runs.

### **Haptic cues for augmented control laws (RCAH, ACAH, TRC, VRC):**

#### **Detents on cyclic and collectives**

- A detent on the neutral position of the collective was considered as very helpful and well designed,
- Mixed feelings were expressed for the detent on cyclics, and its definition more complex. The detent has to be felt, but must not interfere in the stick motions, leading to a more complex and discussed definition of its height and width.

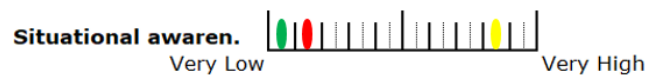
#### **Friction with TRC:**

- Considered as interesting, well adapted for such a law that would be used at low speeds.
- Lateral speed was controlled through the lateral axis and a classical force displacement curve (1N/°). It was asked to have friction also on the lateral axis.

#### **Vibration generated at flight control law change:**

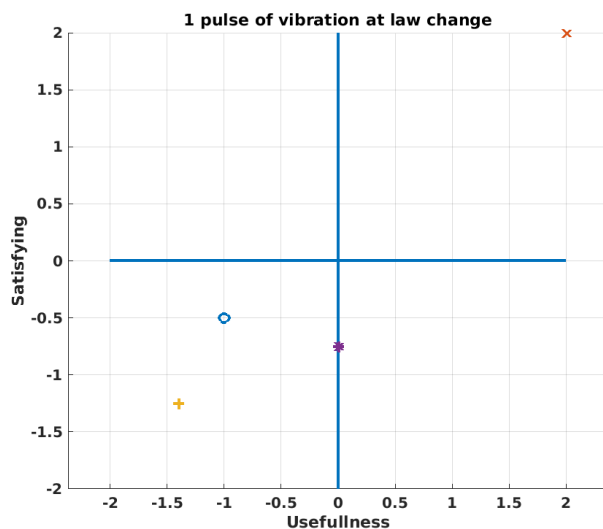
Results show that generating one pulse of vibration at law change is not necessary. The way the flight control laws will be managed (automatically or selected by pilots) can also have an impact on the acceptance of this cue. If pilots select the law, as performing the action it is probably not necessary to add this vibration (and, moreover, the pilot will be hands-off), and if FCS automatically change the law, it depends.

The situational awareness rating for one pulse of vibration at flight control law change is shown hereafter:



The acceptance ratings are presented hereafter, showing poor usefulness and satisfaction (except from one pilot).





**Figure 10. Van Der Laan rating scale for vibration at law change.**

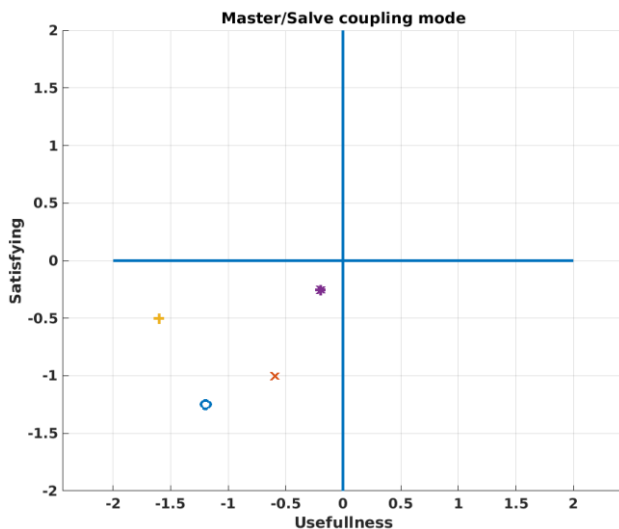
#### **Coupling modes between pilot inceptors,**

- DUAL mode (i.e.: mechanical linkage emulation)

It's the classical and most intuitive mode. A mechanical link has to be emulated leading to identical inceptor positions and motions. This is a recommendation from pilots.

- Master/slave mode:

Potentially used during instruction, at the very beginning. Useless for classic flights.



**Figure 11. Van Der Laan rating scale for Master/slave coupling mode.**

As shown in Figure 11, this coupling mode was badly rated, and by all pilots. First reaction was “oh nice”, but after a short time of reflection, all pilots had doubts and considered this mode as superfluous or even potentially dangerous in case of an emergency to transfer the authority to the slave pilot.

In addition, issues are raised by this mode: the necessity to define a primary pilot, and the necessity to recover the

authority through an additional action on the stick (action on a push-button). The possibility to transferring the authority through another device should also be considered, due to the relative high failure rate of a pushbutton.

- “Asymmetrical” coupling modes

NOT ACCEPTED AT ALL! All pilots found they are useless, bringing confusion.

The “asymmetrical half” mode, requiring to specify a primary pilot to the FCS, brings even more confusion and doubts on “who is on commands”. The fact that motions/positions of both inceptors can be different is not acceptable for pilots.

The “asymmetrical max” was the worst graded mode, leading to the unawareness of the small actions performed by the other pilot, and generating large inceptor motions once the forces are transferred.

Thanks to the “asymmetrical min” mode, limiting the displacements of the co-pilot classical center stick could be interesting in current cockpits, but even this feature is not needed in case of small side-sticks. In addition, it inhibits large control inputs done by one pilot to be felt by the other, decreasing the situational awareness of the controls.

- Decoupled mode:

The possibility to decouple is considered mandatory with the use of active inceptors. This function must be provided, especially in case of ASSU failure. This function is also especially required on tandem cockpit configuration.

#### **Logics to switch from one coupling mode to another**

Selection of the mode has to be done through PFD but no logics based on push-button. Selecting the coupling mode on PFD is sufficient and clear. In addition, the coupling mode would certainly be defined/selected at ground before flight and probably never changed in flight.

#### **Authority transfer / coupling mode change in case of ASSU failure**

As the failed inceptor is locked in position, it is necessary to manage the coupling differently.

At the ASSU failure, if:

The decoupled mode is engaged: no need to change the coupling mode or authority, controls sent to FCS are those from the designated primary pilot.

In Master/slave mode: no coupling or authority change as the force control based law enables PF to manage the flight.

In DUAL mode, one ASSU failure lead to the lock of all inceptors. The failed stick is switched to force control while the functional one, still in position control based logic, remains locked. The failed stick, generating pseudo positions, can send controls to FCS while the functional stick is unable to move. If the pilot whose stick is functional wants to take control, by pressing the authority transfer push-button, (s)he can automatically decouple the sticks and becomes the designated primary pilot.

An automatic decoupling was not considered as it implies that the designated primary pilot have to be in capacity to

take control immediately. As the capability to continue the flight is offered thanks to the force control based law, it was assumed that the transfer of authority could be done on pilot request.

The authority can be taken by the functional stick (through push-button), in this case an automatic decoupling is performed.

It was also concluded (and implemented) that the pilot whose inceptor was failed could take the authority back as the force control based law is available.

Once again, designating a primary pilot through a “take-over” push-button was the logic followed in the project in case of decoupled mode, but the logic applied in Airbus airliners could also be used.

### Force fight decoupling:

Automatic decoupling in case of “force fight” between pilots is not recommended. It generates a large transient in the controls when the coupling is “cut”, even when the force threshold is relatively low as it was tested here (25N). Other studies proposed some solutions (counter force generation) to limit this transient [1] but during our evaluations, pilots found that this feature is useless, even in case of instruction flights. Based on their experience, force fight on linked controls almost never happens. This has to be clearly differentiated from potential dual inputs on decoupled sticks, which is another situation, and that is already managed in Airbus airliner cockpits for example.

### ASSU back-driven by the AFCS when upper modes are engaged

- No back-drive: helicopter pilots prefer to see the flight controls moving, as it’s already the case in helicopters, as the sticks are back-driven through trim actuators.
- Back-drive based on FCS flight commands: Not so realistic in terms of stick motions. Providing the sensation that a system is back-driving the stick, but not a pilot.
- Back-drive based on the “underlying” flight control law: ACAH “like” was preferred, more corresponding to pilot actions (e.g. ASSU inclined on the right during a right turn). This should be considered if this logic is applied while the RCAH law is engaged. In this case, a transition/fading law should be applied when the AFCS is giving back the controls to the crew.

### The authority transfer between pilots and between crew and AFCS

- Between pilots: push-button + vibrations
- The possibility to transfer the authority from one pilot to the other through a “take-over” push-button was very well accepted, and the two pulses of vibrations considered as very useful to know that the transfer has been really done.

The situational awareness for two pulses of vibrations authority transfer was very well rated by all pilots:



It was also confirmed that, as the transfer of authority is done by pressing a push-button (or any other HMI), the pilot who press the button **TAKES** the authority, not the other way around. The possibility to give the authority is not acceptable, as the other pilot might not be capable to “receive” it.

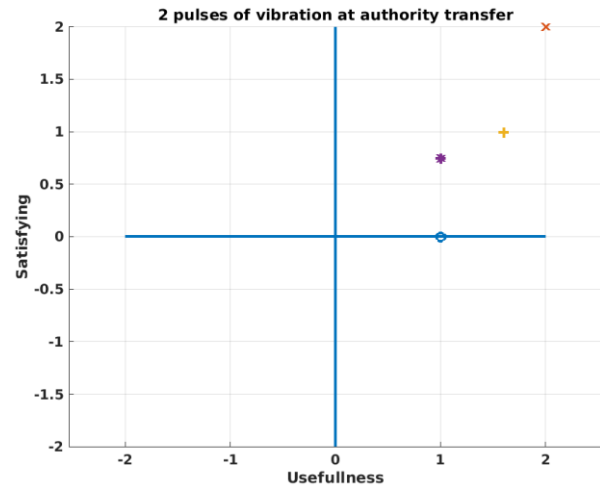


Figure 12. Van Der Laan rating scale for 2 pulses of vibrations at authority transfer.

- Between AFCS and crew: warning light + vibrations
- Feedbacks were mitigated when considering the generation of a vibration at auto-pilot upper mode engagement. As this requires an action to engage the mode, it’s not necessary to add a vibration (and as being hands-off the vibration will probably not be felt) for some pilots. For other pilots, it’s a way to be sure that the mode is really engaged (from system point of view, the vibration must be generated based on AP engagement, and not only based on an action on push-button).

For auto-pilot upper mode disengagement: well accepted by airliner pilot, as there’s already 3 audio “tones” when AP disengages (in Airbus airliner at least).

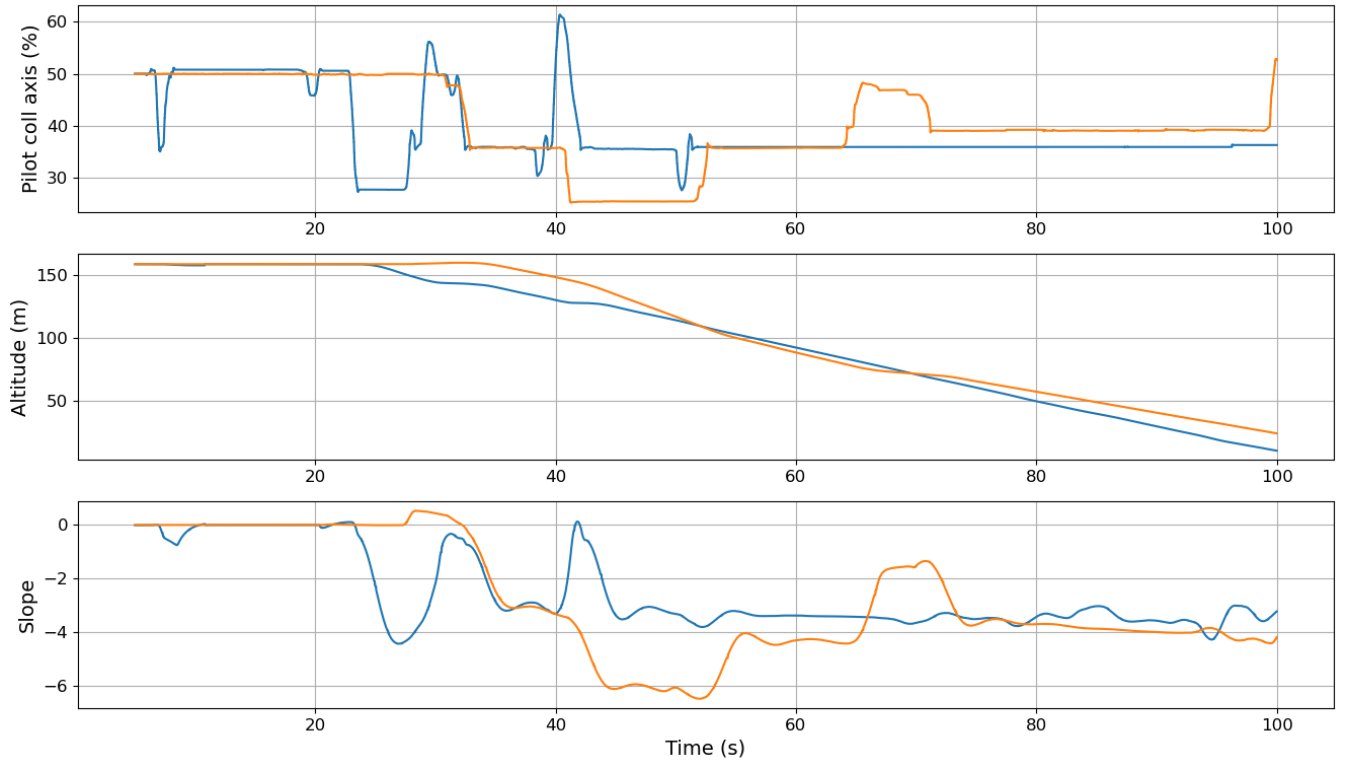
### Flight Envelope Protection functions (FEP)

- Glide slope following
- Providing such a cue eased the task (that is already not so difficult in Visual Meteorological Conditions). The proposed function could be improved, by giving the possibility to deselect it through a push-button when very close to landing. Although following the -3 degrees slope is an easy task, and facilitated by the use of the VRC law (a collective position corresponding to a vertical speed), one can see on Figure 13 and Figure 14 the impact of the haptic cue on the pilot performance. Upper plot show collective position of the collective, the middle plot shows the altitude variation, and the lower plot the glide slope reached during the maneuver. Figure 13 shows the slope and the evolution of the altitude with the haptic cue being active. Comparing to Figure 14

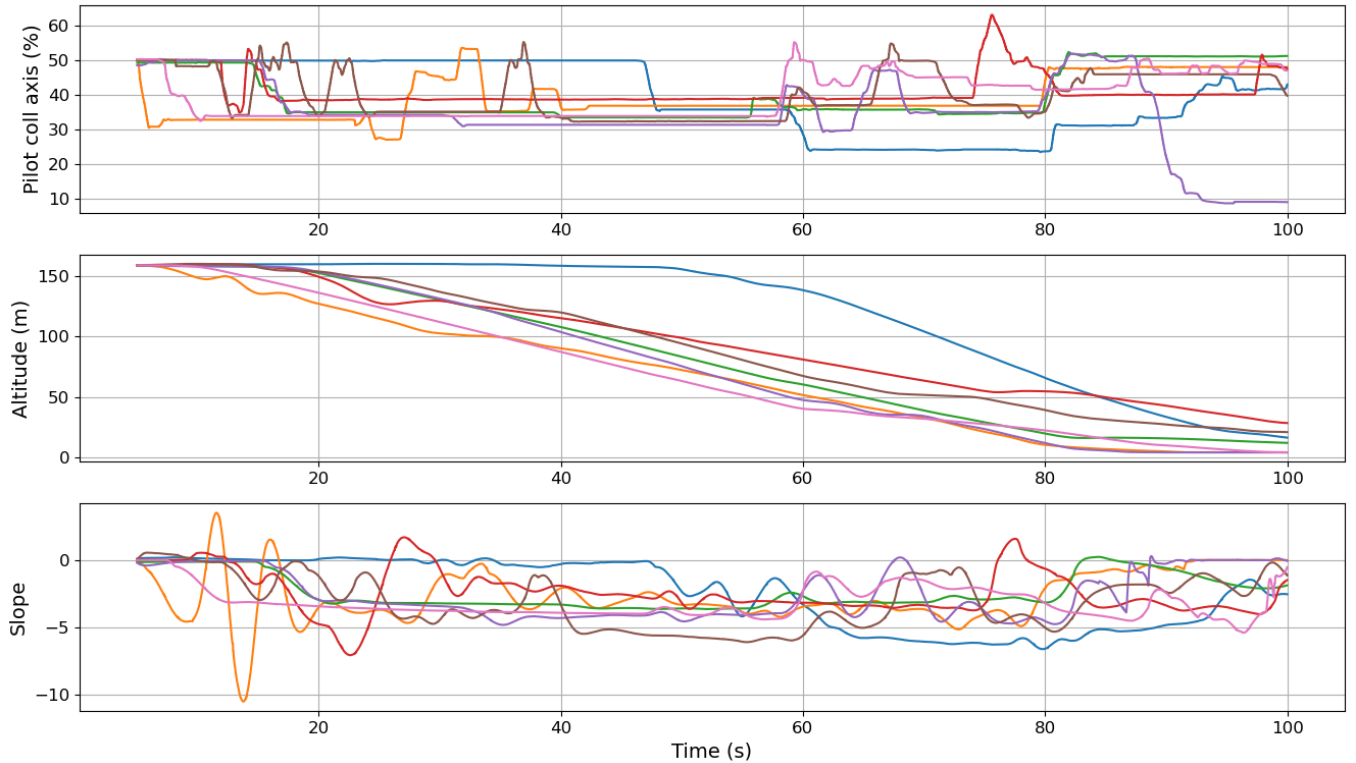


without the detent on the collective, one can see that the slope variations tend to be higher without the detent, as well as the collective stick activity. One can however also notice

that some runs without the detent show very good performances, which can be explained by the efficiency of the VRC control law for this kind of tasks.

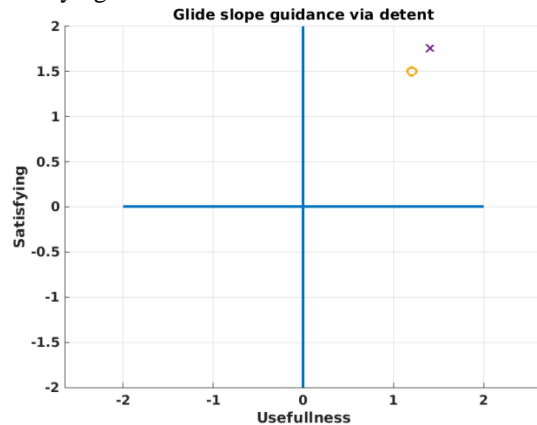


**Figure 13: Pilot collective position, altitude and slope of the tilt-rotor for landings with glide slope detent.**



**Figure 14: Pilot collective position, altitude and slope of the tilt-rotor for landings without glide slope detent.**

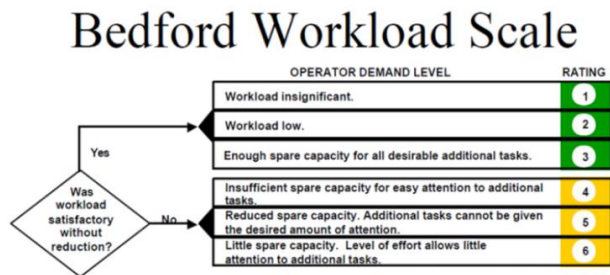
Van der Laan acceptance ratings for such a function were very satisfying:



**Figure 15. Van Der Laan rating scale for glide slope guidance haptic cue.**

In addition to Van der Laan ratings, Bedford workload rating scale was used to estimate the impact of the use of such a guidance function on the workload.

Without function, pilots estimated the workload to 3, while using the guidance function reduced the estimated workload to 2.



**Figure 16. Bedford Workload Scale for glide slope guidance haptic cue.**

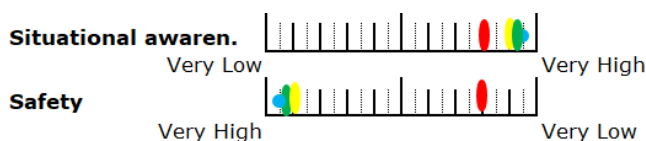
- Corridor

Generally well accepted (as shown in Figure 17), the function led to a lot of feedbacks and improvement proposals for vibration cues.

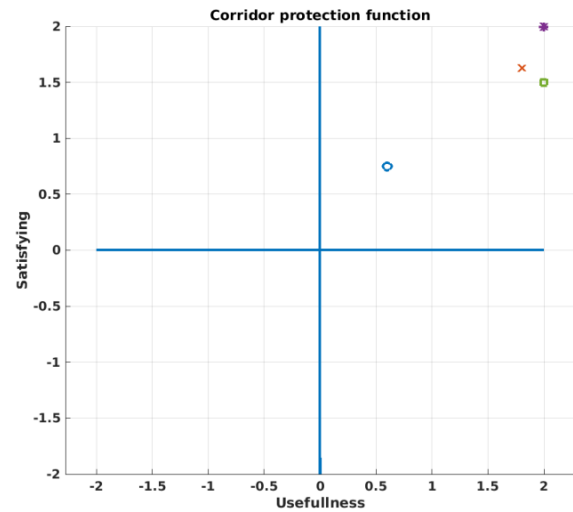
It was always requested that in case of a forward QF increase, the pilot has to be in capacity to override the force gradient.

The rearward trim positioning of the stick was considered as being too high, conducting to a too large deceleration. It should be tuned to bring the machine back to the maximum authorized speed, not less.

The situational awareness and safety ratings for corridor protection function are shown here:



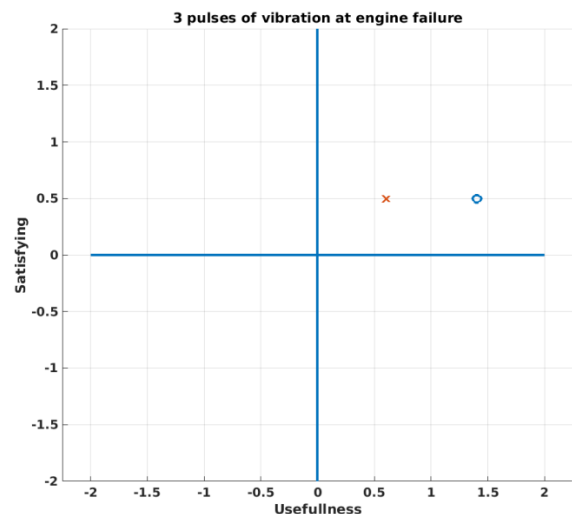
One pilot gave a low rating for safety because he was wondering if, as the function is defined at the moment, it could generate a cognitive overload and an increase of the workload.



**Figure 17. Van Der Laan rating scale for Corridor protection function.**

**Failures of aircraft components, AFCS or ASSU:**

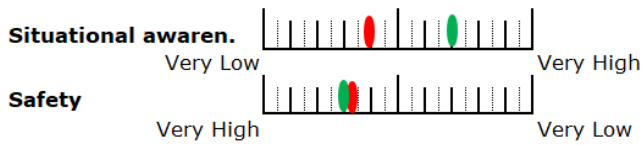
- One engine failure warning through 3 pulses of vibrations generated on the collective



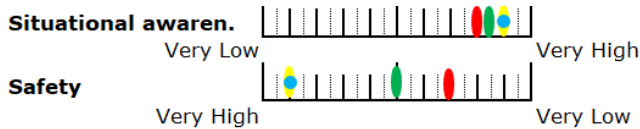
**Figure 18. Van Der Laan rating scale for one engine failure haptic warning.**

This function can catch pilot's attention, but the pilot might not have his hand on the collective, and not feel the vibrations. In addition, many warnings already exist for this situation, making this function superfluous for some pilots, and contributing to rather acceptance results of limited value as shown in Figure 18.

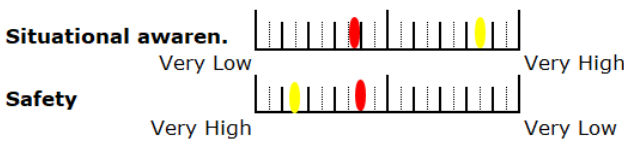
The situational awareness and safety ratings were also mixed:



- AFCS failure warning through 3 pulses of vibrations  
The generation of vibration on the defected AP upper mode axis (e.g. in case of IAS disengagement, vibration generated on longitudinal cyclic axis) was tested.  
The situational awareness and safety ratings for three pulses of vibrations at AFCS failure are given hereafter:  
At take-off:



In cruise:



The pilot will probably be hands-off, especially in cruise phase, mitigating the efficiency of the function if the vibrations are generated only at the AFCS disengagement (discussed after). In addition, sounds due to vibrations might be covered by machine/cockpit sounds.

So, specific runs were performed to evaluate the best moment to generate the vibrations: at AFCS failure and disengagement or malfunction detection by the system. Generally, disengagement of an AP mode is annunciated by flashing an amber message on the PFD during 5 to 10 seconds, before becoming steady once disengaged. This type of functionality was integrated in the simulator, providing steady amber message first, then a red alert message once AP disengaged. It was mostly agreed that vibrations should be generated 5 to 10 seconds after the malfunction detection by the system or, to put the matter differently, 5 to 10 seconds before effective AFCS disengagement.

In such a case, the pilot would be first alerted by the visual warning on PFD, and as leading to a potential AFCS disengagement, would be hands-on and ready to take control, enable to feel the stick vibrations when generated. This led to quite good pilot acceptance ratings as shown in Figure 19:

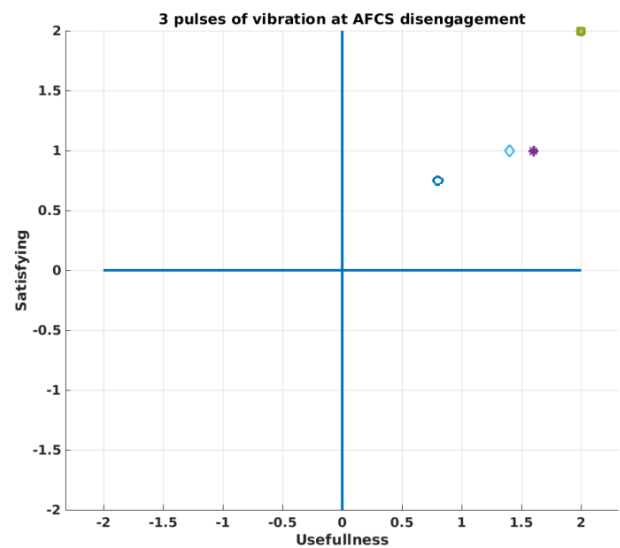


Figure 19. Van Der Laan rating scale for AFCS failure haptic warning.

- ASSU failure: force control law + 3 pulses of vibrations  
Switching automatically from position to force control is mandatory in case of ASSU failure (and thus ASSU lock). The current force control laws could certainly be improved (by using nonlinear laws for example), but they already provide the capability to continue the flight, or land safely. This can be seen on figures Figure 20 and Figure 21, representing the attitudes of the tilt-rotor during the phases where the failure occurs. To simplify the analysis, all figures are presented so that the failure occurs at a time  $t=0$ . In both cases, several runs are plotted on the same graph (each with different color), and they all show acceptable values of roll and pitch angles, even after the failure. Finally, in Figure 21, which are runs of the scenario 2, the landing was successful in most cases (PF trying to perform the landing without transferring the authority to PM).  
The most difficult part of the ASSU failure for the pilot is the transition between positions to force control logic (the pilot applying too high forces at the beginning).

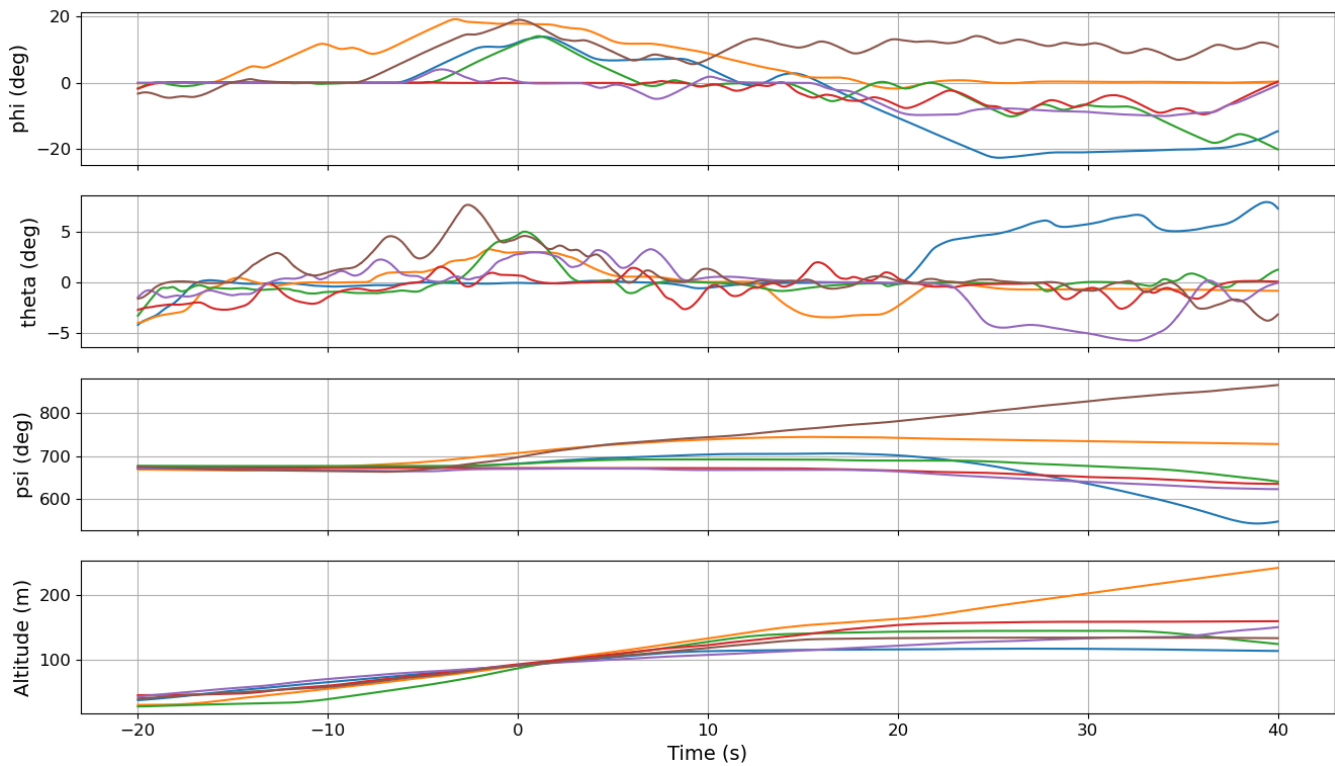
Pilot activity on controls is shown in scenario 1, with ACAH in Figure 22, in scenario 2 with RCAH in Figure 23. The two upper plots shows the longitudinal and lateral forces applied on ASSU, the two lower graphs showing the ASSU positions. Before the ASSU failure, applied forces are relatively low, leading to moderate ASSU position variations. In both situations, after the ASSU failure (after 0s), it can be clearly seen that the pilots apply quite high forces on the grip (while positions remain almost constant). As the DUAL coupling mode was selected between pilot and co-pilot sticks, the copilot stick positions before the ASSU failure are the same than pilot stick positions. After the failure, the pilot forces are transferred to copilot sticks, leading to strong position variations. This can be seen in Figure 24 during runs in scenario 2, with RCAH.

This transition in pilot activity at ASSU failure can be also seen on Figure 25 and Figure 28 with RCAH in scenario 2 and scenario 1, with ACAH in Figure 26 and Figure 27 in scenario 1 and 2.

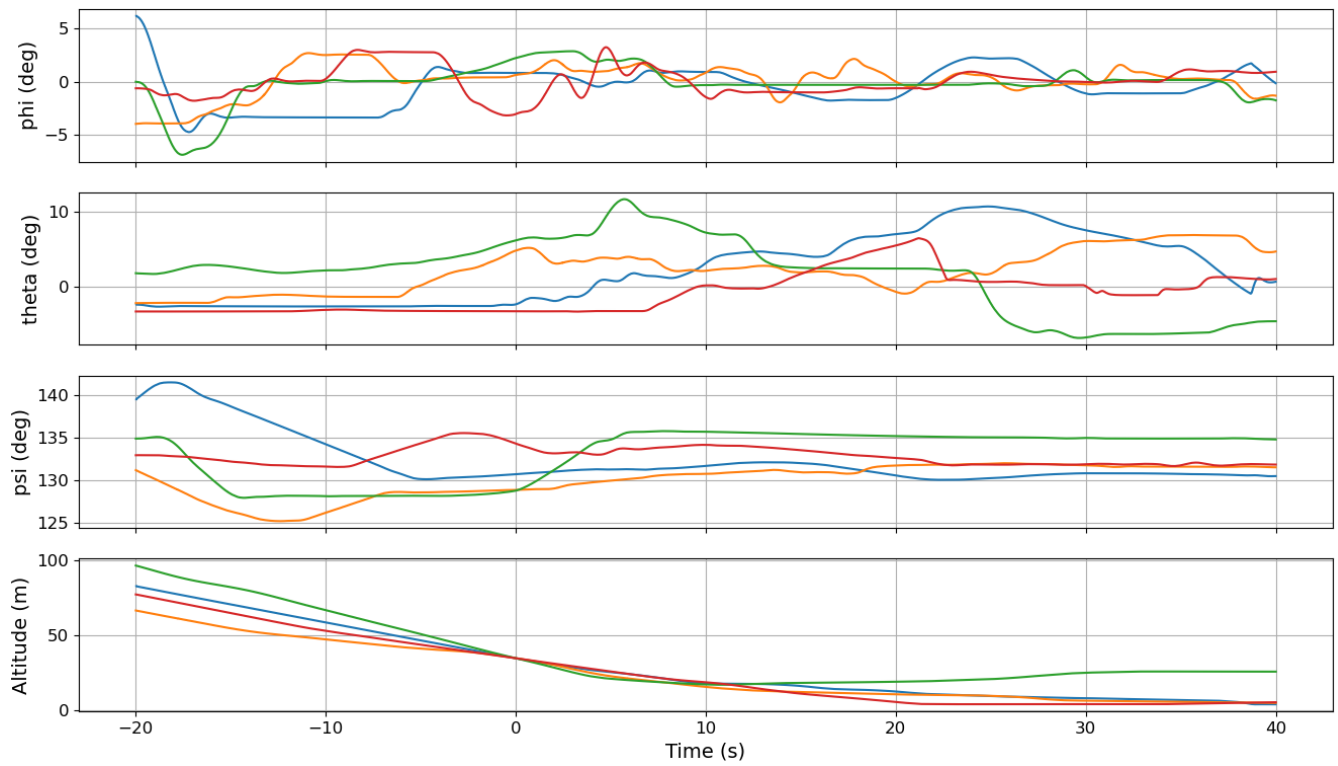
These figures show the forces applied by the pilots during three phases: before the failure, during the 20 seconds after the failure, and 20s after the failure to the end of the run. The forces applied before the failure are moderate, with a mean force applied of 1.82N, while the forces applied right after the failure far exceed what would normally be accepted, with a mean value of 3,27. Then, 20 seconds after the failure, the efforts drop to a mean value of 2,45N. During the first 20 seconds, pilots realize that the ASSU has failed and

often over react. They soon understand that the machine is responsive and therefore adapt and lower their efforts.

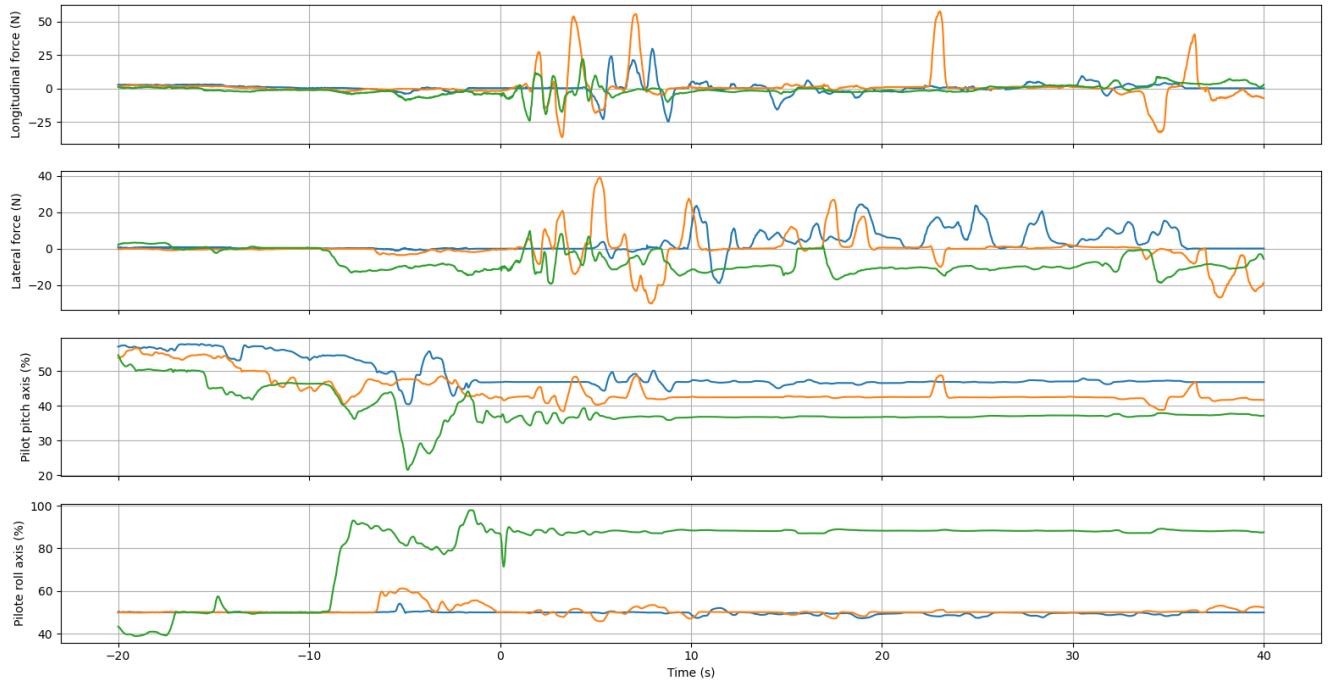
This lead to the conclusion that a transition logic should be studied in order to dim the impact of the preliminary overreaction, if it is still present after training. Nevertheless, while the experimented laws could be improved, and would require more training, they already offer the possibility to continue the flight without the need to transfer the authority to the other pilot. In addition, ACAH flight control law was generally preferred in this situation. The fact that if the forces applied on sticks are released, the aircraft attitudes are set to 0 being safer, even more so in Instrument Meteorological Conditions and/or poor visual cue environments.



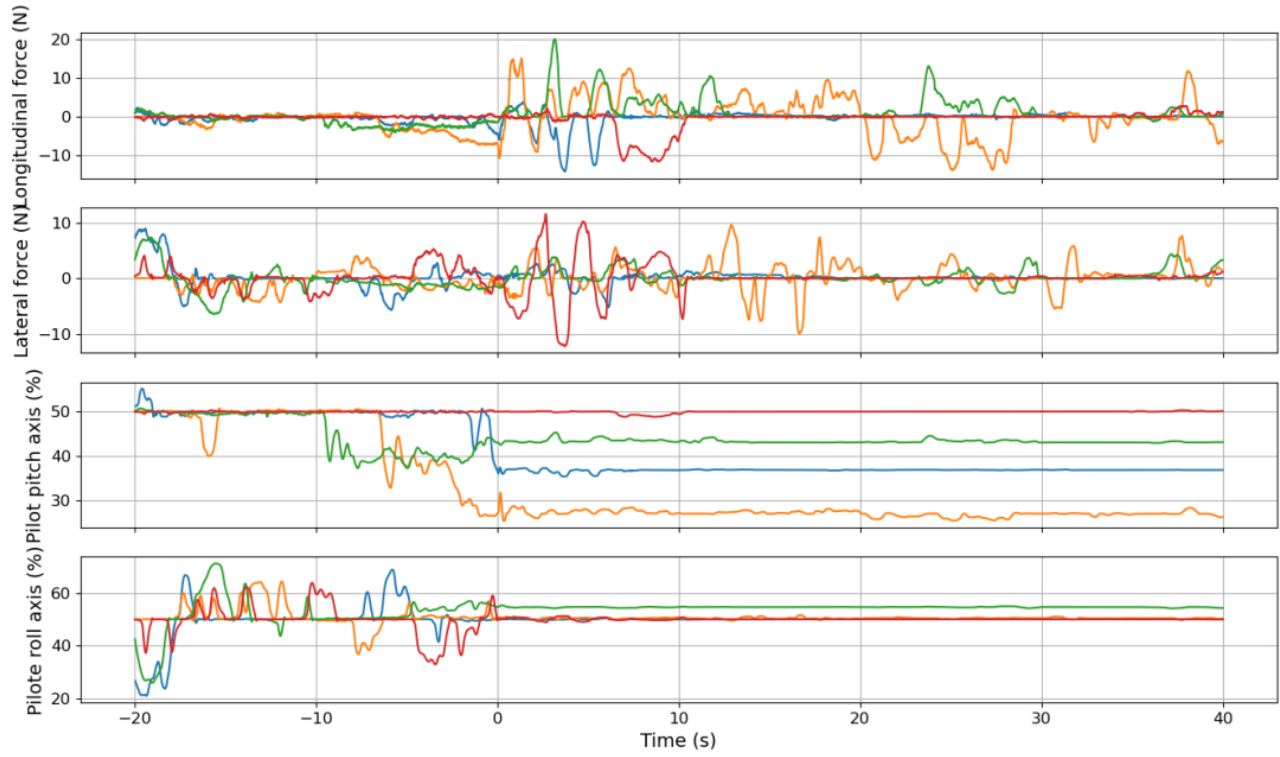
**Figure 20: Attitudes of the tilt-rotor for the scenario 1 (Take-Off), with a failure at  $t=0$  in ACAH**



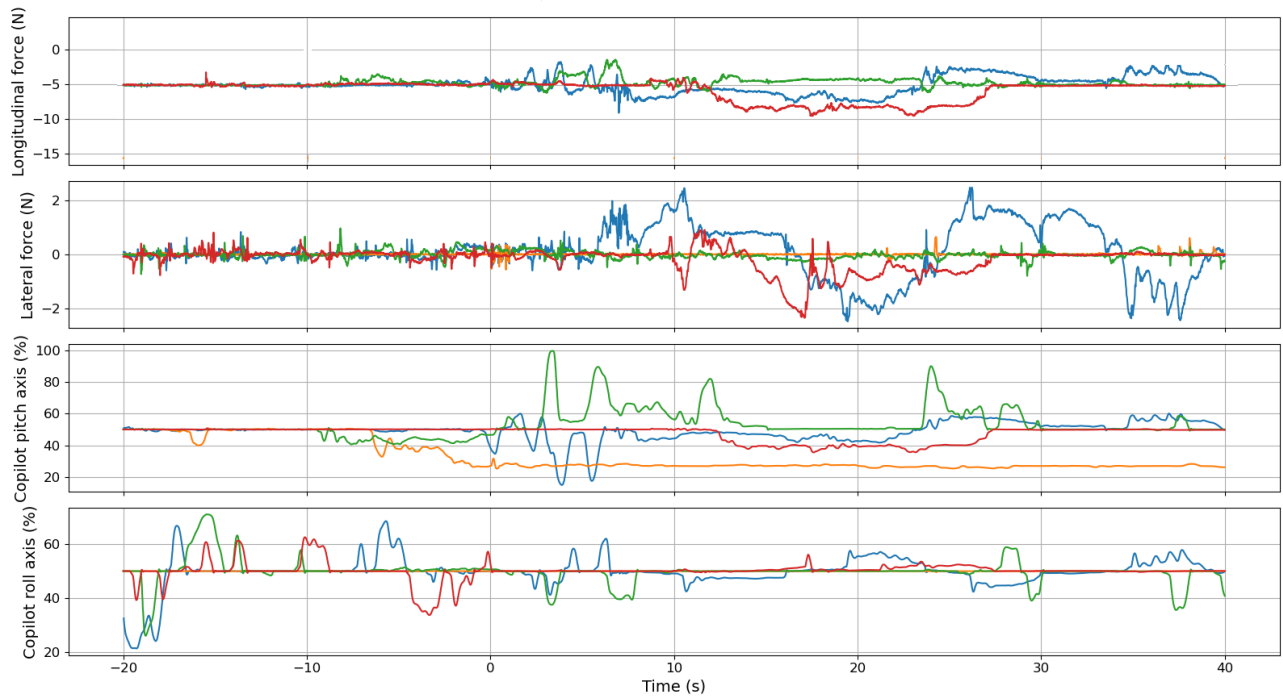
**Figure 21: Attitudes of the tilt-rotor for the scenario 2 (Landing), with a failure at  $t=0$  in RCAH**



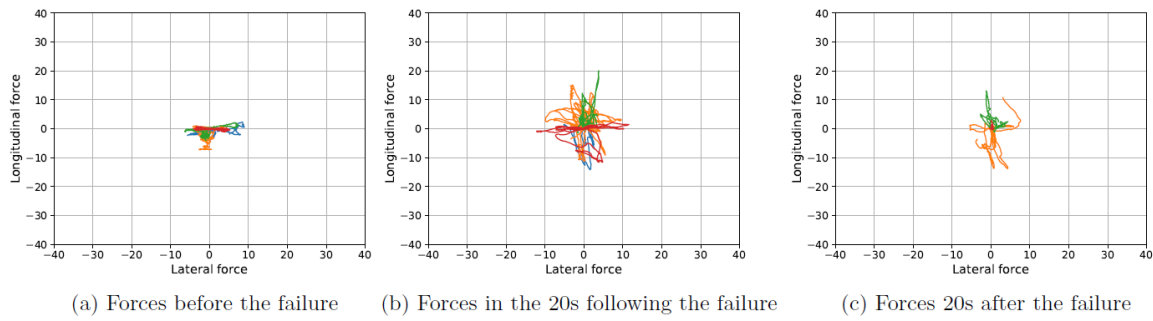
**Figure 22: Pilot cyclic stick activity in scenario 1 in ACAH**



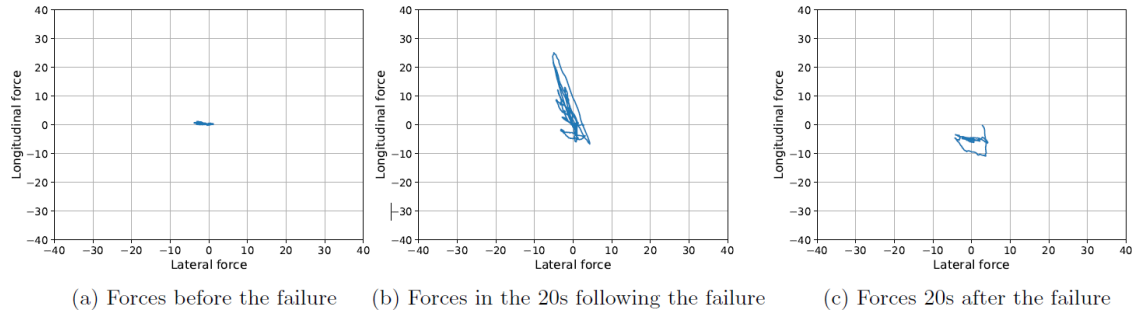
**Figure 23: Pilot cyclic stick activity in scenario 2 in RCAH**



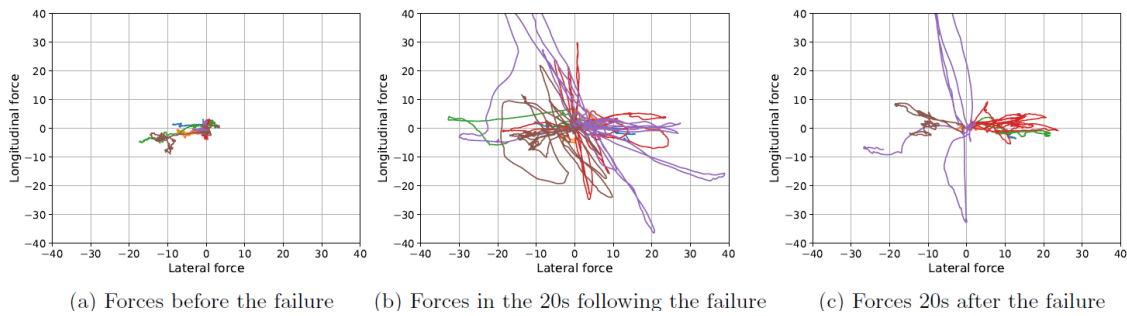
**Figure 24: Copilot stick activity in scenario 2 in RCAH**



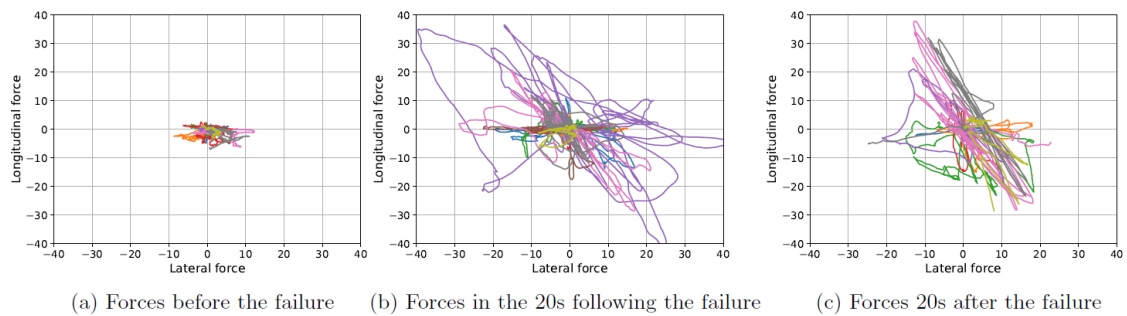
**Figure 25: Forces applied to the pilot stick in RCAH during scenario 2**



**Figure 26: Forces applied to the pilot stick in ACAH for scenario 1**



**Figure 27: Forces applied to the pilot stick in ACAH for scenario 2**



**Figure 28: Forces applied to the pilot stick in RCAH for scenario 1**

#### ASSU Failure warning through vibrations on the remaining ASSU:

The generation of three pulses of vibration at ASSU failure occurrence was well appreciated by pilots.

Pilots admit it provides information that something is going wrong. As it's a failure, generating three pulses is coherent with the logic followed in the project. Correlating these

vibrations to warning lights and/or audio sounds would be even more alerting, even if it already increases situational awareness. But, as always mentioned during the evaluations, vibrations will not always be felt because PM is generally hands-off.

It was supposed here that vibrations could be only generated on the remaining functional ASSU. But pilots asked if this



could be done also on the failed (mechanically locked) inceptor.

General considerations on vibration used as haptic cues warnings:

**One** vibration for status change (AP mode engagement/disengagement, flight control laws, coupling change, etc.): generating a vibration for each status change could be confusing, and potentially not felt in hands-off situations.

**Two** pulses of vibrations for authority transfer was the most well accepted cue. In this case, all pilots are supposed to be hands-on, ensuring the vibrations will be felt.

This vibration could be even generated if the pilot, who already has the authority, presses again the authority transfer push-button.

**Three** pulses of vibrations for any failure based on the same logic when pilot says “failure, failure, failure”. Three pulses bring the attention back inside the cockpit and can’t be confused with “natural” aircraft vibrations.

Recommendations from pilots: The best logic would be to correlate the number of vibration to the existing Advisory / Caution / Warning alerts applied for the corresponding situation.

In this respect, synchronizing vibrations with existing audio warnings (more specifically in airliners) and/or visual indicators would increase their alerting capabilities.

General results: Best is the enemy of the good, and providing too much haptic feedbacks can lead to the loss of the meaning and efficiency of these cues.

Pilots want to have an efficient, highly robust and intuitive inceptor system. Having the sensation of controlling another, additional, system is prohibitive.

The same conclusion can be drawn for inceptor coupling modes that have to be simple, intuitive and leading to identical inceptors’ motions when coupled.

General remarks: The results might be tempered by the fact that the evaluations were performed in a fixed based simulator, a quiet and calm room, and the cockpit didn’t proposed all the potential visual displays or audio warnings that can exist on-board real machines.

In addition, vibrations were mainly heard instead of being “felt”. Thus, some warnings using vibrations could alert while the pilot was hands-off. This would not be the case in real flight conditions and environments.

Discontinuous vibrations would be certainly better felt and understood as very different from existing aircraft vibrations.

Vibrations have to be felt when hands-on but must not interfere with pilot controls.

## NEXT STEPS OR IMPROVEMENTS

Feedbacks from very experienced pilots are always a source of information on the current on-board systems and, depending on the new functions or logics tested, a source of

inspiration for future developments. Therefore, it is thus planned to continue to work on the improvement of the current tested functions, or the development of specific new piloting aids suggested by pilots during the trials:

When inceptors are back-driven by upper AP modes, smoothing ASSU position when flight control law is changed by AFCS would be requested. In addition, as the stick motions emulating ACAH law were generally preferred and better interpreted, a fading function should be developed to ensure the transition between the inceptor positions and the flight control law (if RCAH) when the upper modes are disengaged.

As shown in the paper, the force control laws could be improved, and a investigating a smooth transition law between position to force control based laws would be recommended.

Moreover, if the coupling modes accepted by pilots were the DUAL and decouple modes, investigating the function necessary to perform a smooth transition between these modes is requested.

While not part of the project objectives, the use and management of augmented control laws (TRC, ACAH or RCAH) were frequently discussed during the trials. In this project, it was considered that the flight control laws could be selected by crew on the primary flight display. Some studies were previously performed by aircraft manufacturers, where the capability to automatically switch from one law to another, depending on flight case and/or pilot actions on controls was analyzed. Depending on the logic followed (automatic switch by FCS or manual selection) the associated haptic cues could be different and differently appreciated.

Finally, most of helicopter pilots are accustomed to the use of “fly through” functions if upper AP modes engaged. But while these functions were implemented in the simulator, they were not tested. Some improvements of these functions, specific experiments and investigations could be interesting to be led.

## ACKNOWLEDGMENTS

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## CONCLUSIONS

This paper summarizes a 42 months project in which more than 400 hours of discussions and meetings, preliminary tests and final evaluations were conducted with very experienced pilots.

In addition to the development of a civil tilt-rotor model and the expected on-board flight control systems (upper autopilot modes and augmented flight control laws), four scenarios were defined, enabling the evaluation of PF/PM and crew/AFCS interactions and leading to the development of a large number of haptic functions, coupling mode or logics. These features were finally evaluated by, at the moment, 7 pilots and a total of 40 hours of simulator trials. Additional simulator trials and evaluations will be performed up to the end of the project, in end of May 2022.

While active inceptor technology offers the possibility to create specific coupling modes, where the forces transferred between ASSU can be not symmetrical, the main result certainly consists on the non-acceptance by pilots of the "asymmetrical" or "Master/slave" coupling modes. The only coupling modes acclaimed by pilots remain the DUAL (mechanical linkage emulation) and the decouple modes. This second one, could be selected before flight in case of single pilot operations, or requested in flight in case of one ASSU failure.

In addition, generating one pulse of vibration at status changes (flight control law, AP modes, etc.), or three pulses of vibrations at failures (engine, ASSU or AFCS modes) offered more discussions and more mixed results. The main questions being that the vibrations can only be felt in hands-on situations, that their level should be adapted to real cockpit environments, and their associated sounds that could be heard in the simulator would be certainly inaudible in real machines.

On the other hand, the possibility to transfer the authority from one pilot to the other, highlighted by the generation of two pulses of vibrations, was very well graded and accepted by pilots. The increase of situational awareness and sense of safety this function provides was unanimously recognized as well as an improvement in crew coordination.

ASSU failure was investigated and the automatic switch from position to force control logics assessed. The proposed force control laws could be improved, but the overall results were good, as the force control laws could be managed to continue the flight without the need of an authority transfer to the other pilot. The possibility to maintain the coupling between a failed and a functional inceptor was also very well appreciated, offering to the pilot whose stick is failed to see his actions on the other stick, and allowing the other pilot to feel the actions performed by the pilot on the failed stick.

A glide slope guidance and a corridor protection functions were evaluated and showed an increase of situational awareness and workload reduction.

In most of the cases, the proposed solutions bring to situational awareness, safety and crew coordination improvement and the decrease of pilots workload.

It has to be outlined that results are highly dependent on the machines and systems that pilots are used to fly, and the flight cases and procedures or missions they regularly experience.

Finally, this project enabled ONERA to mature a dual cockpit configuration research simulator integrating now a large number of systems and functionalities that will be continuously improved in the next years.

## REFERENCES

1. Sampaio, R.S., "Electronic coupled active sidesticks in dual pilot helicopters for instructional flights," Proceedings of the AIAA Modeling and Simulation Technologies Conference, Vol. 1, 2013.
2. Uehara, A. F. and Niedermeier, D., "Limited Evaluation of the Influence of Coupled Sidesticks on the Pilot Monitoring's Awareness during Stall in Cruise," Proceedings of the AIAA Modeling and Simulation Technologies Conference, Vol. 1, 2013.
3. Jeffrey W Hegg, Marion P Smith, Honeywell Inc., Space Systems, Clearwater, FL 34624, Larry Yount, Honeywell Inc., Air Transport Systems, Glendale, AZ, John Todd, McDonnell Douglas Corp., Douglas Aircraft Company, Long Beach, CA. "FEATURES OF ACTIVE SIDESTICK CONTROLLERS", IEEE, 1994 .
4. Bureau d'Enquêtes et d'Analyses pour la sécurité de l'aviation civile (BEA), "Final Report on the accident on 1st June 2009 to the Airbus A330-203 registered F-GZCP operated by Air France flight AF447," France, July 2012.
5. Dr.-Ing. Burgmair, R. Alford, A. Mouritsen, S. "Definition and verification of active inceptor requirements for a future tiltrotor," 31<sup>st</sup> European Rotorcraft Forum, Florence, Italy, September 13-15, 2005.
6. Binet, L. "Versatile Offline Simulation Tool for Systems Design," 47<sup>th</sup> European Rotorcraft Forum, United Kingdom, September 7-9<sup>th</sup>, 2021.
7. J.D. Van Der Laan, A. Heino, D. De Waard, "A simple procedure for the assessment of acceptance of advanced transport telematics", Traffic Research Center, University of Groningen, P.O Box 69, 9750 AB, Haren, The Netherlands.