Influence of Variable Inceptor Coupling on Dual Pilot Helicopters using Active Sidesticks

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To my family.

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Abstract

Safety reports indicate that the control transfer between the pilots near the ground can lead to loss of control accidents. This controllability problem is recurrently associated with control interferences during takeover control performed by the flight instructor in helicopter training flights. Since the standard flight control system features mechanical coupling between pilot's and copilot's flight controls, an inceptor decoupling system was not available. As an alternative to the mechanical linkages across the cabin, the next generation of fly-by-wire helicopters can be equipped with electronically coupled active sidesticks.

In order to address the controllability problem, this research aims to investigate how electronically coupled active sidesticks can assist pilots during takeover control in dual pilot helicopters. The following scientific contributions are deemed to achieve the research aim. 1. Validation of the electronic inceptor coupling system for helicopter demands. 2. Development of an appropriate concept for the coupling and definition of parameter ranges, which allow the alleviation of the common transient effects as control overshoot and attitude oscillations. 3. Demonstration of the ability of the active sidesticks to support the flight instructor to takeover control in low level flight.

The realized concept of the variable inceptor coupling allowed to electronically couple and decouple the inceptors according to the pilots' needs, either manually (pushbutton) or automatically (force threshold). Overall, nine pilots (seven of them test pilots) participated in three flight test campaigns in a dual pilot helicopter simulator with electronically coupled inceptors. Within these campaigns, the influence of the variable inceptor coupling was evaluated on the following aspects: situation awareness, pilot acceptance, pilot workload, helicopter flying qualities and helicopter controllability.

The electronically coupled inceptors were found to contribute positively to situational awareness of the flight instructors in the selected helicopter scenarios, especially regarding the ability to project future states of the helicopter. Moreover, findings confirmed the possibility to mitigate transient control overshoots due to the automatic inceptor decoupling through the implementation of a force fading logic. Consequently, this logic showed to be effective to alleviate helicopter attitude oscillations. This effect was also observed for a second helicopter configuration with poorer handling qualities. For the analysis of the optimum region of the decoupling force threshold, a new methodology was proposed, which combined quantitative and qualitative data. The optimum force threshold range was indicated as the interval between 20 N and 30 N in pitch axis, which showed to be high enough to avoid inadvertent decoupling and low enough to avoid safety degradation beyond handling qualities level 2 by limiting the transient effects. Lastly, findings indicated that both manual and automatic inceptor decoupling functions reduced the control activity in case of control interference. Also, pilots considered the decoupling functions useful, predictable and easy, whereby successful takeover control maneuvers were performed in lower levels of perceived workload compared to the configuration without inceptor decoupling.

Kurzfassung

Bei der Steuerübergabe zwischen den beiden Piloten in einem zweisitzigen Hubschraubercockpit kann es laut Untersuchungsberichten zu Flugunfällen durch Kontrollverlust, engl. *loss of control*, kommen. Dieses Problem trat wiederholt während des Schulungsbetriebs beim Eingreifen des Fluglehrers auf. Dabei spielte der Umstand eine Rolle, dass die konventionellen Flugsteuerungssysteme mechanisch sind und sich die Steuer von Pilot und Copilot sich nicht entkoppeln lassen. Als Lösung für dieses Problem könnte in zukünftigen *fly-by-wire* Hubschraubern aktive Steuerorgane verwendet werden, welche nicht mechanisch über Steuergestänge, sondern elektronisch gekoppelt und entkoppelt werden können.

In der vorliegenden Arbeit wurde untersucht, wie elektronisch gekoppelte aktive Steuerorgane die Piloten bei der Kontrollübergabe in einem zweisitzigen Hubschraubercockpit unterstützen können. Dazu wurden die folgenden Beiträge geleistet: 1. Validierung der elektronischen Steuerkopplung für Hubschrauberanforderungen. 2. Entwicklung eines geeigneten Konzepts zur Kopplung und Definition von Wertebereichen, welche die bei einer Steuerübergabe auftretenden unerwünschten transienten Effekte wie Steuersprünge oder Oszillationen des Hubschraubers auf ein akzeptables Minimum beschränken. 3. Demonstration der Fähigkeit den Fluglehrer bei der sicheren Steuerübernahme im bodennahen Flug zu unterstützen.

Das umgesetzte Konzept zur variablen Steuerkopplung erlaubt je nach Bedürfnis der Piloten entweder eine manuelle (Drucktaste) oder automatische (Kraftschwellenwert) Entkopplung, engl. *decoupling*. Insgesamt neun Piloten, davon sieben Testpiloten, nahmen an drei verschiedenen Studien in einem zweisitzigen Simulator mit elektronisch gekoppelten aktiven Steuern teil. In diesen Studien wurde der Einfluss der elektronisch gekoppelten Steuer auf das Situationsbewusstsein, die Piloten-Akzeptanz und die Arbeitsbelastung, sowie die Hubschrauberflugeigenschaften und die -Steuerbarkeit untersucht.

Es wurde festgestellt, dass die elektronisch gekoppelten Steuer in den gewählten Szenarien positiv zur Situationswahrnehmung der Fluglehrer beitragen, insbesondere

hinsichtlich der Fähigkeit, zukünftige Zustände des Hubschraubers zu projizieren. Darüber hinaus zeigten die Befunde folgendes: Es ist möglich, das im Moment der Steuerentkopplung auftretende transiente Überschießen und die sich anschließenden Hubschrauberoszillationen zu verringern, wenn die Kopplungskräfte zwischen den verbundenen Steuern nicht plötzlich deaktiviert, sondern verlangsamt ausgeblendet werden, engl. *fading*. Dieser Effekt traf auch auf eine zweite Hubschrauberkonfiguration mit schlechteren Flugeigenschaften zu. Für die Ermittlung des optimalen Bereiches für die Kraftschwelle zur automatischen Entkopplung wurde eine Methodik vorgestellt, welche quantitative und qualitative Daten kombiniert. Die optimale Kraftschwelle, welche sowohl hoch genug ist, um ein unbeabsichtigtes Entkoppeln zu vermeiden als auch niedrig genug um die transienten Effekte auf ein akzeptables Maß zu beschränken liegt bei 20 N bis 30 N für das Nicksteuer. Schließlich zeigte sich, dass sowohl die manuelle als auch die automatische Funktion zur Entkoppelung die anschließende Pilotenaktivität zur Stabilisierung des Hubschraubers gegenüber dem Referenzfall ohne Entkopplungsmöglichkeit reduzierte. Außerdem betrachteten die Piloten die Entkopplungsfunktionen als nützlich, vorhersagbar und einfach verständlich. Dabei bewerteten die Piloten die subjektive empfundene Arbeitsbelastung für die Konfigurationen mit Entkopplungsmöglichkeit als niedriger gegenüber der Referenzkonfiguration.

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Abbreviations:

2PASD	Dual Pilot Active Sidestick Demonstrator
AC	Advisory Circular
ACAH	Attitude Command Attitude Hold
ACT/FHS	Active Control Technology/Flying Helicopter Simulator
ADS	Aeronautical Design Standard
AGL	Above Ground Level
AIAA	American Institute of Aeronautics and Astronautics
AIS	Active Inceptor System
ANOVA	Analysis of Variance
AOPA	Aircraft Owners and Pilots Association
ASRA	Advanced Systems Research Aircraft
ATIC	Advanced Technology Institute of Commuter
AUTO	Inceptor Coupling Configuration including Automatic Decoupling
AVES	Air Vehicle Simulator
BENCH	Permanently Coupled Inceptor Configuration
CAA	Civil Aviation Authority
CAN	Controller Area Network
CFR	Code of Federal Regulations
Config.	Inceptor Coupling Configuration
CPU	Computer
DLR	German Aerospace Center (*Deutsches Zentrum für Luft- und Raumfahrt*)
DOF	Degrees of Freedom
DSS	Decision Support System
DVI	Digital Visual Interface
EASA	European Aviation Safety Agency
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FBW	Fly-by-Wire
FCC	Flight Control Computer
FCMC	Force Control Mechanical Characteristics
FCS	Flight Control System

FG	Facilitating Goals
FH	Flight Hours
FI	Flight Instructor
FOV	Field of View
FRP	Finger Reference Point
FT	Force Threshold
GM	Gain Margin
GmbH	Private Company (*Gesellschaft mit beschränkter Haftung*)
HDMI	High Definition Multimedia Interface
HMC	Human-Machine Cooperation
HQ	Handling Qualities
HQR	Handling Qualities Rating
HSD	Honest Significant Difference
HUD	Head-up Display
IHST	International Helicopter Safety Team
INT	Control Interference
LED	Light-Emitting Diode
LOC	Loos of Control
LOC	Loss of Control
MI	Managing Interference
MIL-STD	Military Standard
MTE	Mission Task Element
NASA	National Aeronautics and Space Administration
NOE	Nap of the Earth (Flight Navigation)
NRC	National Research Council Canada
NTSB	National Transportation Safety Board
NVG	Night Vision Goggles
OEI	One Engine Inoperative
OFE	Operational Flight Envelope
PF	Pilot Flying
PFD	Primary Flight Display
PFD	Pilot Flight Display
PIO	Pilot Induced Oscillation
PIOR	Pilot Induced Oscillations Rating
PIOR	Pilot Induced Oscillation Rating
PM	Pilot Monitoring
PSD	Power Spectral Density
PUSH	Inceptor Coupling Configuration including Manual Decoupling
R&D	Research and Development
RASCAL	Rotorcraft Aircrew Systems Concepts Airborne Laboratory
RC	Rate Command
RMS	Root Mean Square

ROC	Receiver Operating Characteristics
RPM	Rotation per Minute
SA	Situation Awareness
SAFO	Safety Alert for Operators
SAGAT	Situation Awareness Global Assessment Technique
SCM	System Control Module
SFE	Safe Flight Envelope
SQ	Sub-Aspects of the Main Scientific Question
STFT	Short Time Fourier transform
TFR	Time-Frequency Representation
TLX	Task Load Index
TR	Transient Rating
TR	Transient Rating
TUBS	*Technische Universität Braunschweig*
UK	United Kingdom
UNCP	Uncoupled Inceptor Configuration
US	United States
USB	Universal Serial Bus
USMC	United States Marine Corps
VMS	Vertical Motion Simulator
VRS	Vortex Ring State
WTD	Technical and Airworthiness Center for Aircraft (*Wehrtechnische Dienststelle*)

Roman Symbols

a, b, c, d	Cross tabulation Values for McNemar Statistical Analysis
A	Matrix
b	Damping Coefficient, kg/s
C	Celsius (Unit of Temperature)
cm	Centimeter (Unit of Distance)
d	Distance, mm
D	Damping Ratio, -
dB	Decibel
deg	Degree (Unit of Angle)
det	Determinant (Algebra)
df_b	Degrees of Freedom between Groups (ANOVA)
df_w	Degrees of Freedom within the Groups (ANOVA)
F	Force, N
Fb	Breakout Force, N
F_{Fn}	Force Feedback to Pilot n, N
F_n	Force applied by Pilot n, N
ft	Feet (Unit of Distance)
g	Acceleration of gravity, m/s^2

hPa	Hectopascal (Unit of Pressure)
Hz	Hertz (Unit of Frequency)
I	Imaginary Number
k	Force Deflection Gradient, N/%
kg	Kilograms
kt	Knots (Unit of Velocity)
m	Stick Inertia, kg
mm	Millimeter (Unit of Length)
ms	Millisecond (Unit of Time)
n	Total Number of Discordant Pairs
N	Newton (Unit of Force)
N	Total Answer in Cross-Tabulation McNemar Statistical Analysis
p	Significant value (statistics)
p,q,r	Aircraft Angular Rates, deg/s
p.	Page
pp.	Page Range
r	Arm, mm
rad	Radian (Unit Of Angle)
r_{FRP}	Reference Finger Point Arm (sidestick), mm
r_{RP}	Reference Point Arm (pedal), mm
s	Second (Unit of Time)
t	Time, s
t_d	Dual Input Time, s
t_f	Force Fight Time, s
t_i	Initial Time, s
u, v, w	Aircraft Airspeed Components in the x, y and z Directions, ft/s
x	Deflection. mm
x	Number of Discordant Pairs (McNemar Statistical Analysis)
x, y, z	Directions (Body-Fixed Axes)
x_{max}	Maximum Deflection, mm

Greek Symbols

δ	Control Deflection, % or mm
δ_{Fn}	Control Deflection Feedback to Pilots, % or mm
δ_n	Control Deflection of Pilot n, % or mm
δ_R	Resultant Deflection to FCS, % or mm
δ_x	Deflection in X-Axis, % or mm
δ_y	Deflection in Y-Axis, % or mm
θ	Theta (Pitch Angle), deg
λ	Eigenvalue, -
τ_d	Time delay, ms
φ	Angular Displacement, deg
ϕ	Phi (Roll Angle), deg

ω_{180}	Frequency where phase angle is -180 deg, rad/sec or Hz
$\omega_{BW_{gain}}$	Gain Bandwidth Frequency, rad/sec or Hz
$\omega_{BW_{phase}}$	Phase Bandwidth Frequency, rad/sec or Hz
ω_n	Natural Frequency, rad/sec or Hz

1 Introduction

1.1 Motivation

In the fly-by-wire (FBW) helicopter, all commands and signals are transmitted electrically via wires, allowing the total elimination of the complex mechanical linkages in the flight control system (FCS). This design offers a number of enhancements over conventional controls for rotorcraft, as reduced cost and weight, improved reliability, elimination of mechanical anomalies, and relief of spatial constraints [1], [2]. The pilot inceptor controls the helicopter in a full-authority FBW system through the redundant flight control computers (FCC). These computers determine the servo hydraulic actuators movement of the helicopter to achieve a fast, well damped response throughout the flight envelope[1] [3, p. 181]. The terminology "inceptor" indicates any device that is used to provide pilot's control inputs. It can be divided into two basic types – passive and active.

The passive inceptors only provide a fixed force–displacement relationship by means of a mechanical spring-damper arrangement. There is no active, real time control of the stick feel characteristics or tactile feedback to the pilot [4]. Moreover, along with the removal of the mechanical linkage to the actuators, the cross cockpit coupling of the inceptors (pilot-copilot sticks) was also eliminated. Thus, if the pilot moves the sidestick, the copilot's sidestick will remain static and vice-versa, which can be problematic to understand the actions of pilots on control. An alternative to this cross cockpit coupling problem is the reintroduction of fairly complex and heavy mechanical linkages between the passive inceptors. However, the characteristics described in the next paragraph indicate that it may be a suboptimal solution.

The mechanical linkages can reduce or even negate some meaningful advantages of FBW designs, regarding weight, mechanical complexity, direct maintenance costs, reliability, and flexibility in cockpit design [5]. In the case of the Airbus A320, the inceptor mechanical coupling was not adopted to prevent friction, backlash, and inertia;

[1] The flight envelope of an aircraft is the strict limits in which the controllability and structural integrity is guaranteed without early design degradation.

and also to avoid the introduction of single failures that could affect both sidesticks, thereby requiring a separation system [6].

In this context, the active inceptor system (AIS) emerged as an evolution of passive flight controls for the next generation of FBW aircraft. This system provides a wide range of force–deflection characteristics by computer controlling force motors which back-drives the control stick [3]. Through the ability to provide synthetic mass-spring-damper feel in real time manner, the AIS can mimic the force deflection characteristics of a mechanical linkage [4]. Indeed, the coupling of inceptors for dual pilot control through electronic connection, as opposed to the traditional mechanical linkage, is one of the most significant capabilities of the AIS. The corresponding inceptor position in both control stations generates tactile force feedback to the pilots at the grip, which is provided by the sidestick control computer using high bandwidth actuators in an active manner [7].

Collinson [3, p. 245] states that the ability to couple the inceptors in different control stations is seen as a major advantage compared with their uncoupled counterparts. He highlights the relevance to trainer and transport aircraft, where both the pilot and co-pilot can be fully aware of each other's actions, much in the same way as with mechanically coupled traditional control inceptors, without the complexity entailed with mechanical cross-feeds.

It should be emphasized that no FBW helicopter featuring active coupled sidesticks has obtained civil certification yet. Currently, all FBW helicopters are restricted to prototypes used in research and military projects. Since FBW helicopters featuring electronic inceptor coupling did not achieve initial operating capability, the complete understanding of this design in service is yet to be attained. Nevertheless, the imminent introduction of active inceptor brings about new inquiries, such as the capability of the new coupling system to provide adequate pilots' situation awareness and to assist pilots in takeover control maneuvers, which are addressed in this thesis. There is a scarcity of studies dedicated to answering these questions, especially regarding the rotary wings field. The present work intends to fill in this scientific gap.

1.2 The Active Coupling Significance to Takeover Control

The inceptor cross-cabin coupling influences directly the ability of the pilots to takeover control by overpowering the inceptors, i.e., applying more force than the other pilot. In this maneuver, the pilot monitoring (PM) acts on control to takeover from the pilot flying (PF)[2]. Since both inceptors are in the same position with respect to their neutral points, the takeover control will start as soon as the PM counteracts the PF's control inputs by applying force on the stick [8].

In the event of takeover control in active inceptors, the closed loop will provide a virtual electronic coupling and will use both inputs (PM and PF) to produce the position that corresponds to the summed forces [4]. When the pilots push in different directions, the coupling feature allows the pilots to engage in a force fight [7]. The force feedback[3] of the coupled inceptors is valuable information for the PM to adjust the inceptors to perform an effective takeover control; and it is equally significant to the PF, who must recognize the overriding input to timely relinquish inceptors.

The effect of coupled inceptors on the PF's response time (i.e., reaction time) was investigated by Zaichik *et al.* [10] in the simulator for the A320 aircraft. One pilot flew a landing approach and the other pilot interfered by starting a go-around by pressing the priority button in case of uncoupled sidesticks or by merely overriding control in case of coupled sidesticks. Using the uncoupled sidesticks, the pilot continued the landing approach as long as 10 seconds after the interference, relying only on the aircraft reaction. In the coupled configuration, the response time to recognize the other pilot interference decreased to two seconds.

Summers *et al.* [11] also examined the introduction coupled sidesticks to A320 aircraft in a fixed based simulator. Likewise, they concluded that, in the event of overriding maneuvers performed by the PM without prior information, the response time of the PF was lower with the coupled sidesticks compared to the uncoupled ones. The pilots preferred coupled sidesticks because they could obtain force feedback through the control stick and the forces communicated a sense of urgency.

Field [12, p. 175] indicates that tactile cues from the inceptor coupling inform the pilot that a change has been commanded before the change occurs. Due to aircraft dynamics, the change may not occur for a second or two after the command has been made. So, the tactile feedback of an inappropriate input may be a faster indication of the unsafe condition than the aircraft response to this input. This feedback is meaningful in demanding tasks, when the pilots' attention is often focused outside the cockpit and the PM rests hands on the inceptors to monitor performance of the PF. The

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[2] In a two-pilot operation, one pilot is designated as PF and one pilot is designated as PM. The PF is person who has controls of the aircraft. The PM monitors the flight management and aircraft control actions of the PF, and also carries out support duties such as communications and check-list reading.

[3] *Force Feedback* is the mechanical production of information that can be sensed by the human kinesthetic system [9].

tactile cues of the inceptor coupling were found to provide useful anticipatory knowledge to the pilots in determining his/her own control strategy in commercial aircraft flights [13].

The findings of the previously mentioned research are deeply associated with the significance of the force feedback provided by the active inceptor coupling. The force feedback information can be encoded and processed by humans due to the ability to distinguish force, movement, position, displacement and joint angle during the operation of the inceptor. The human holistic perception of the arrangement of the limbs and other parts of the body is called kinesthetic[4] sensibility [14]. Coupled inceptors provide the possibility to obtain a direct kinesthetic feedback to detect the other pilot inputs, which is commonly used by pilots as a shared cue to monitor the pilot performance, teach piloting techniques and maintain flight safety. Thus, the coupling of the inceptors is an important part of the cockpit error management, especially in flight training or emergency situations [10]. It provides significant amount of information that pilots receive from each other's inceptor movements [17].

1.3 The Control Transfer Problem

In the preceding paragraphs, the terms PM and PF were used to define the crew in a dual pilot helicopter cabin. These terms are universally accepted and frequently mentioned in previous works, thus they are included herein. However, these words might raise confusion for the control transfer case, since the pilots swap roles after this procedure. To avoid this risk, the PM and PF will be preferably referred to as flight instructor[5] (FI) and trainee pilot, respectively. Although the action of control transfer is a common procedure in all types of flights, the instructor-trainee case provides an easy identification of who is taking over control. As the ultimate responsible for safety in the training flight, the FI usually needs to adjust the position of the helicopter, which justifies recurrent control interferences.

Typically, a verbal interaction is employed to transfer control between the pilots. In non-time-critical conditions, the FI requests the control before any interference on the

[4] *Kinesthetic* is a term that is often used interchangeably with *haptic* and *tactile*. In ISO 9241, *haptic* is a broad field used to describe everything based on sense and manipulation of touch, and comprises of two subclasses: *tactile* and *kinesthetic* [14]. While *kinesthetic* refers to sense and motor activity based on muscles, joints and tendons; *tactile* is closely related to recognition through skin (cutaneous sense) [15], [16]. However, the terms *haptic* and *tactile* are generally accepted as replacements in most dictionary definitions [14].

[5] The flight instructor is the person responsible to teach how to fly a particular model of aircraft [18].

inceptors, which is generally accepted by the trainee pilot, who relinquishes control to complete the procedure. The trainee pilot response time corresponds to the time required to recognize and react to the control transfer requested by the FI. A command and response "I have control/ you have control" is the standard communication to ensure that both pilots are aware of the control transfer.

However, in emergency or high demanding situations, insufficient time to announce the control transfer may arise. According to the comprehensive safety analysis in [19], the action of takeover control without prior notice should be immediately assessed if pilots need to deal with unforeseen or unsafe conditions. Abrupt changes of aircraft attitude, dangerous atmospheric disturbances, and unexpected obstacles or warnings may justify a sudden interference in control [10]. In these conditions, the actions of both pilots must be clear, and the cross-cockpit coupling can contribute to the prompt recognition of the pilots' intentions.

Figure 1.1 illustrates the FI-trainee pilot interaction in the non-time-critical and the time-critical conditions.

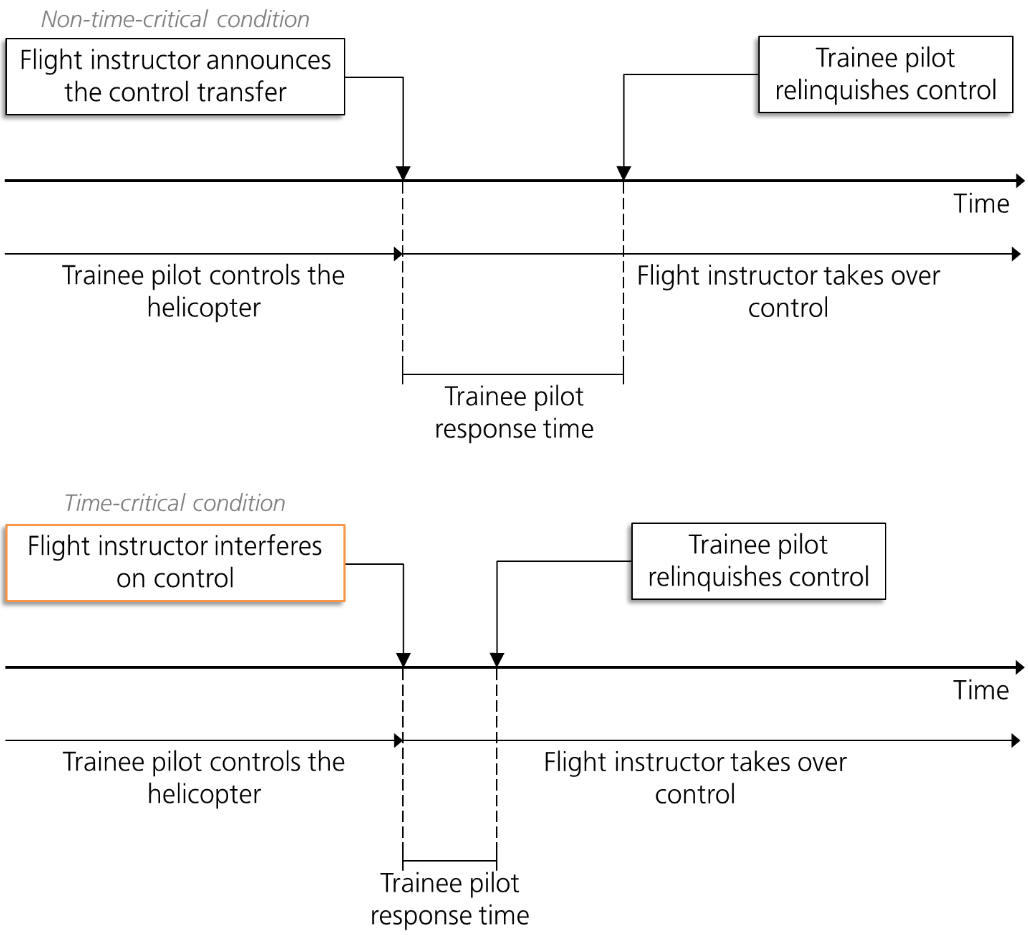

Figure 1.1: Control transfer procedure in non-time-critical (upper) and time-critical (lower) conditions

In order to minimize the trainee pilot response time, the announcement of the control transfer is replaced by the immediate interference on control in the time-critical condition, which may be effective in some cases, but also may lead to control difficulties in other situations.

In this context, the inceptor coupling across the cabin is intrinsically associated with two problematic aspects: the impact on the ability to monitor the trainee pilot performance (before the control transfer) and the helicopter attitude transients (after the takeover control maneuver).

Impact on the Ability to Monitor the Trainee Pilot's Performance

The active coupled inceptors influence directly the ability of the FI to monitor the performance of the trainee pilot in helicopter flights, which is a key feature to allow timely FI's interventions on control. The electronic inceptor coupling certainly conveys extra information to the pilots concerning the manual control inputs being made. However, it is not clear if the FI would be able to use this information on behalf of his/her situation awareness in helicopter scenarios.

In a rare study addressed to rotorcraft environment, Burgmair *et al.* [20] analyzed the link performance of two electronically coupled active inceptors for tiltrotor applications. Procedures to transfer, prioritize and limit control were performed in a BO-105 ground simulator. However, the position and force synchronization of the two cyclic sidesticks was judged to be insufficient for helicopters, due to a time lag of 150 ms between the sidesticks. The study does not offer an analysis for dual pilot issues; neither does it assess the effectiveness of electronic linked inceptors. Hence, the application of the electronic coupling to helicopter domain is still an open issue.

It should be mentioned that novel technologies to increase awareness have been subject to much criticism concerning ambiguous, misleading and contradicting information [20], [21]. Therefore, the investigation of the electronic inceptor coupling is necessary to validate the ability of the system to support the monitoring task of the helicopter FI, which is one of goals of this thesis.

Impact on the Pilot Controllability and on the Helicopter Attitude Transients

The transients in helicopter attitude caused by the control transfer can trigger loss of control (LOC) accidents. This category of helicopter accidents is frequently indicated in investigation reports and named as 'control interference' [22], [23], [24], [25]. These occurrences are largely characterized by the intervention of the FI in control and the failure of the trainee pilot to recognize the interference. Additional causes may be related to inceptor jam of any nature or obstruction of inceptors by an object.

In these accidents, the helicopters were equipped with mechanical linkages between the inceptors. Even if the pilots were able to recognize the interference in a few seconds, this brief interference could still trigger inadvertent control inputs, attitude oscillations and helicopter loss of control. In some cases (as the ones that will be described in the Chapter 3), the acknowledgment of the trainee pilot about the takeover control maneuver can take longer than usual. Pilot inexperience, channelized attention, and difficulty to perform the task in progress are some aspects that can influence the response time of the pilot in command [22]-[25]. Additionally, it is strictly recommended that the trainee pilot releases the inceptors only after the positive recognition of the FI's readiness to control the aircraft. This recognition can delay even more the control transfer and increase the risk of the maneuver, because both pilots are temporarily trying to fly at the same time.

The challenging outcome caused by the interference during takeover control maneuver is illustrated in Figure 1.2. The plots refer to a flight condition described in an accident investigation report [25] and reproduced in simulator using electronically coupled AIS. At time = 0, the FI counteracts the pitch down input of the trainee pilot. In the example, the trainee pilot relinquishes control in less than two seconds (arrow 1). This action triggers an overshoot in the inceptor position, because the force to counteract the trainee pilot is now transferred to the deflection of the stick according to the force-deflection curve (arrow 2). The stepwise control input causes significant helicopter attitude variation in high attitude rate (arrows 4 and 3, respectively). In case of flight near obstacles, the helicopter motion can lead to minimal safety margins or even catastrophic events.

A significant aspect of these LOC occurrences in flight training is that generally the FI was guarding the inceptors before the attempt to takeover control, but s/he still lost the helicopter control. According to aviation agencies, the procedure of control transfer is the cause of numerous accidents [26, p. 10]. Considering that a force fight between the pilots is a potential undesired condition, the electronic coupled inceptors could designate the primary set of flight controls using a decoupling method, as a takeover button or a priority algorithm. In light of the safety challenge, the programmable nature of active coupled inceptors provides feasible conditions to implement a control prioritization to mitigate this category of accidents.

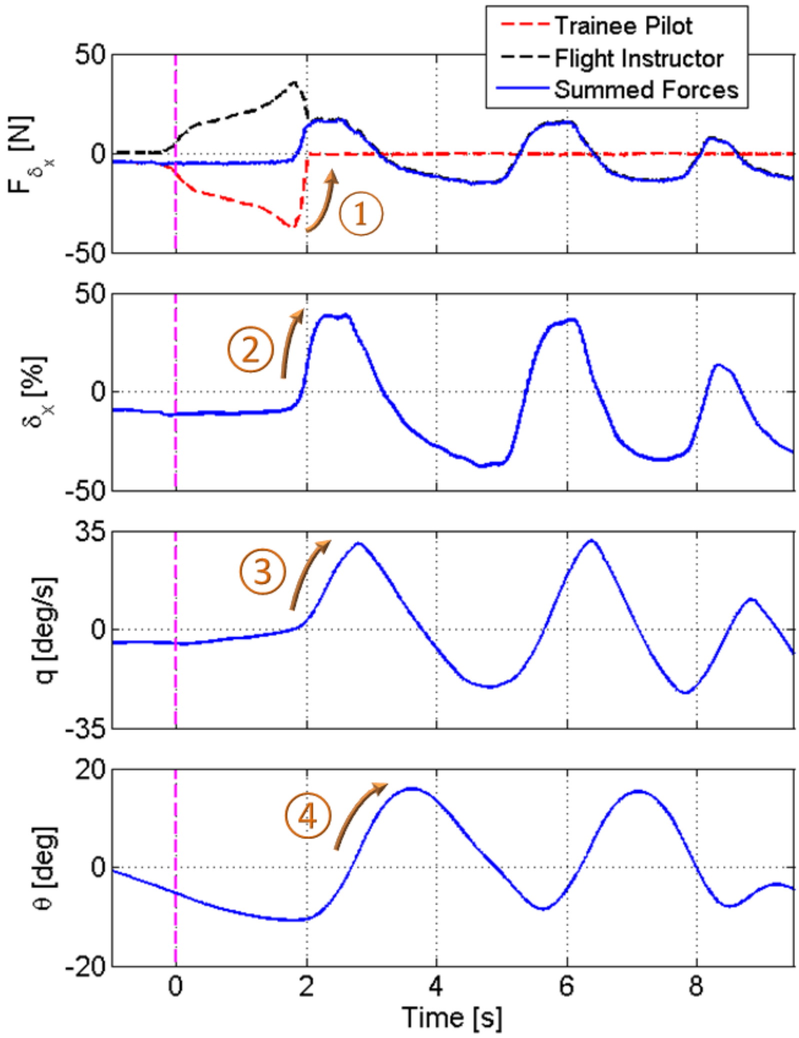

Figure 1.2: Takeover control maneuver

1.4 A Novel Design: Variable Inceptor Coupling

The electronic nature of the AIS enables the development of a flexible coupling of the flight controls, namely variable inceptor coupling, which was developed in the present work. Besides the ability to emulate the mechanical cross-cabin linkage, prioritization logics can be implemented to adapt the helicopter to pilot's needs.

The design of the variable inceptor coupling allows the transition between coupled and uncoupled status to prioritize one control station. The most notable application of this design can be to assist pilots during takeover control maneuvers, which may be effective to avoid the safety problem during control transfer exemplified in Figure 1.2. The introduction of an automatic prioritization function is also possible, through the quantification of the forces and positions of the active inceptors in real time. As a safety relevant function, the ultimate goal is to perform takeover control with minimal consequence to the controllability.

The prioritization functions can still be used to isolate malfunctions in one control assembly, to deactivate the control station of the incapacitated pilot or to disable controls whilst transporting a passenger in the copilot seat.

1.5 Summary of Research Contributions

The present thesis aims to advance the knowledge regarding the ability of the active sidesticks to provide inceptor cross-cabin coupling. The following four contributions to this growing area of research are highlighted below.

1. Validate an electronic inceptor coupling system in active sidesticks for helicopters

To date, there has been no reliable evidence regarding the ability of the AIS to support the helicopter FI to monitor the performance of the trainee pilot. There is a general lack of research about the effectiveness of AIS to provide electronic inceptor coupling applied to dual pilot helicopters. The major references mentioned in the previous subsections analyzed the possibility to implement active couple inceptors geared towards airplane demands, and primarily commercial flights. Kelly and Castillo [27] highlight that helicopters are unique aircraft, with unique safety challenges that may not lend themselves to fixed-wing technological solutions. The meaningful differences in the helicopter flight envelope embrace operations near the ground or obstacles, at slow speeds, or in confined spaces that are not feasible for typical airplanes. Thus, the findings of this research can benefit the development of FCS in future FBW helicopters.

2. Propose an approach to mitigate the attitude oscillations during takeover control by reducing the control activity through adaptive fading force logic in automatic inceptor decoupling

In the event of a force fight between the pilots, a force threshold can be programmed to automatically decouple the flight controls. In order to propose this automatic decoupling function in the variable inceptor system, the present thesis developed a method to alleviate attitude oscillations as the consequence of this function. The problematic is addressed by a force fading function to decouple gradually the inceptors. The potential solution of the automatic inceptor decoupling intends to avoid inaccurate control deflections, but its feasibility has not been proven yet. The underlying hypothesis is that a significant reduction in control and attitude oscillations using the inceptor decoupling system will provide better flight predictability and lower pilot workload compared to the system without decoupling. Due to the relevance of control transfer to flight safety, it becomes pressing to gain insight into this scientific gap to support the implementation of active sidestick functions in dual pilot helicopters.

3. Propose a methodology to develop force threshold envelope in automatic decoupling systems for electronically coupled active sidesticks

The novelty of active technology in helicopter stimulates the development of new methods to determine the limits of the automatic decoupling system. The combination of quantitative flight test data in simulator, subjective transient scale, and statistical analysis provided the basis for the proposal of the optimum force threshold range according to the safety severity outcome. In order to generalize the results, variations of the helicopter dynamic stability allow broader application of the results regarding the force threshold boundaries.

4. Prove the ability of the active sidesticks to support the flight instructor to takeover control in low level flight

A novel design, namely variable inceptor system, is developed to support the pilots during takeover control maneuver in low level flight. To this end, the concepts of human-machine cooperation are used to conceive the variable inceptor system design. The challenging introduction of a decoupling system in active coupled inceptors increases the risk of sudden transients, which is relevant to flight safety. Technical documents clearly forewarn that a stepwise changing in control may be the result of the abrupt decoupling, since the pilots are pushing the grips in different directions [7]. When one control cabin is prioritized, the opposing force of the other control cabin is deactivated, but the prioritized pilot might have to undergo inadvertent control deflection and aircraft attitude oscillations. Since it raises questions regarding the ability of the system to support the pilots during takeover control maneuvers, the present work offers a detailed analysis of these adverse effects. The effectiveness of the decoupling methods is confirmed by its ability to reduce pilot workload and to be considered safety relevant from the pilots' perspective. It should be emphasized that prioritization systems were assessed in the past for passive uncoupled inceptors, but the significance of coupled AIS including decoupling means to dual pilot operation still remains undocumented. By assisting pilots in maneuvers near the ground, the improvements to pilot controllability can contribute to avoid flight accidents.

1.6 Scientific Questioning and Methodology

This research examines the electronic inceptor coupling in a dual pilot helicopter cockpit using active sidesticks. The thesis is dedicated to answer the fundamental scientific question:

How can electronically coupled active sidesticks assist the flight instructor to takeover control in dual pilot helicopters?

In order to answer this higher-level scientific question, the following sub-aspects must be clarified:

SQ1: How is the influence of the electronically coupled active sidesticks on the situation awareness of the helicopter instructor pilot?

The ability of the coupled inceptor system to provide understandable and deterministic feedback to the pilots to predict near-future states of the helicopter is an essential question per se. At the same time, it is also crucial for successful takeover control maneuvers, because it can be taxing to detect errors and intervene timely to avoid an unsafe situation without a shared understanding of the actions on control.

SQ2: What is the optimum force threshold range for the automatic decoupling in instructional flights? Can a force fading logic alleviate the transients influenced by the automatic decoupling?

It is necessary to examine how the variation of the force threshold to decouple inceptors influences the control overshoot and attitude oscillations. Low force threshold can lead to unintentional inceptor decoupling, while high forces can bring about physical effort and control difficulty. So, is it possible to determine an optimum force threshold range for the automatic decoupling? Furthermore, the development of an adaptive fading logic to compensate the opposing forces during takeover control maneuvers is feasible due to the unique ability of the active sidesticks to measure in real time the forces applied on inceptors. The questions are grouped because both aspects are related to the development of the automatic inceptor decoupling system.

SQ3: How does the variable inceptor coupling affect the pilot workload, attitude oscillations and control activity to takeover control in low level flight? How is the pilot acceptance of the variable inceptor coupling for the task of takeover control in low level flight?

The manual and automatic inceptor decoupling are introduced as assistance functions to takeover control. Both decoupling means of the variable inceptor coupling are compared to a permanently linked configuration (benchmark), through the emulation of the mechanical linkage in active sidesticks. The extent to which the decoupling systems affect flying qualities is still unknown, so the analysis of attitude oscillations and control activity is performed. The amount of effort and attention, both physical and mental, that the pilot must provide to attain a takeover maneuver is equally important to flight safety, thus a pilot workload survey is also being investigated. Furthermore, the pilot's perceived usefulness regarding the variable inceptor decoupling is verified. The user acceptance is often the pivotal factor determining the success or failure of technological innovations [28]. Therefore, the factors that influence the pilot's acceptance is undoubtedly important for further development and future implementation of active sidesticks in dual pilot helicopters.

1.7 Thesis Structure

Chapter 2 introduces the main concepts for the active inceptors. The application of the technology to electronically couple the inceptors across the dual pilot cabin is described, along with the relevant aspects of sidestick design. Additionally, a theoretical framework regarding active coupled inceptors applied to helicopters is provided.

Chapter 3 outlines the inceptor coupling significance to flight safety and defines the potential problems that could emerge due to implementation of this flight control design. Initially, the ability of the inceptors to provide force feedback at the stick and to influence the pilot's situation awareness is analyzed. Moreover, the application of the inceptor coupling design to takeover control in flight training is highlighted. Lastly, flight accidents in which the inceptor coupling was present as a decisive contributing factor are discussed.

Chapter 4 describes the variable inceptor coupling and the system design approach. The hallmark of the design consists of the core system (inceptor coupling/ decoupling logic) and of the supplementary structures, which includes the tactile cues, warning, trim, and feel systems. The development of four inceptor coupling configurations to be tested in the experimental evaluations is described within the core system. They are: uncoupled inceptors, permanently coupled inceptors, coupled inceptors including automatic decoupling, and coupled inceptors including manual decoupling.

Chapter 5 presents the experimental setup, including the simulation environment and the helicopter model. The simulator facility was conceived and developed for the present thesis; hence the setup of the test rig is addressed herein. Lastly, the research methodology for the evaluations is introduced.

Chapter 6 describes the results of the situational awareness evaluation. The tests investigate the ability of the electronically coupled active sidesticks to provide understandable and deterministic feedback to the pilots to predict near-future states of the helicopter. A comparative assessment of the uncoupled and permanently coupled sidesticks is performed to analyze the influence of these inceptor designs on the situation awareness (SA) of the FI pilot.

Chapter 7 examines the influence of the automatic decoupling function to the helicopter flight. An analysis of a force fading function to alleviate attitude oscillation post-automatic inceptor decoupling is performed. The force threshold is the method to decouple controls in case of force fight between the pilots. Since high force threshold can lead to control difficulty and low force threshold can cause unintentional inceptor decoupling, the optimum force threshold range for the automatic decoupling is investigated. Lastly, the impact of the inceptor decoupling on the flying qualities is verified.

Chapter 8 presents the results of the comparative analysis of three configurations to the task of takeover control in low level flight. The tested designs include the permanently coupled inceptors and the two variable inceptor coupling alternatives (coupled inceptors with manual and automatic decoupling). Besides the quantitative analysis of the control and the attitude variation after the takeover control maneuver, the pilot workload and pilot acceptance are also investigated.

Chapter 9 outlines the conclusions, contributions and the outlook for future research in the field of active technology applied to flight control system, especially in helicopters.

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2 Technological and Research Review

This chapter presents the fundamental concepts for the active inceptors and the relevant aspects of the sidestick design. The inceptor coupling solutions for active sidesticks are introduced along with the rationale for the electronic cross-cabin coupling. Additionally, the FBW helicopters featuring active inceptors are briefly mentioned. Finally, the theoretical framework regarding active coupled inceptor is provided.

2.1 Active Inceptor System

The AIS typically provides control of stick position as a function of the force sensed at the grip from an input applied by the pilot [29]. The key components of an active inceptor are illustrated in Figure 2.1, which was modified from [4]. The mechanics consists of gimbal assemblies, bearings, and housings connecting the stick to the force and position sensors. The force sensors measure the pilot force input and transmit this signal to a CPU, which calculates the required stick deflections according to a control law. The deflection is generated by electromechanical servo actuator units based on the calculations of the motor drive electronics that incorporate position sensor feedback. The electronics of the AIS units work as the interface between the FCC and the grips, as can be seen in the functional block diagram with the feedback loops in Figure 2.2 [4].

The bandwidth generated by the programmable servo actuators is a crucial aspect of the system to provide the primary control forces felt by the pilot [7]. The haptic quality of the active inceptor is closely connected to the ability to generate high band of frequencies transmitted by the stick system [30]. The bandwidth can be considerably influenced by factors as the mechanical properties (inertia, friction, elasticity) [30] and the latency in the computational processes, which arises from the use of digital computers in the processing of the control laws and sensor data [3, p. 208]. The active inceptor coupling bandwidth has been demonstrated to be higher than the frequencies normally involved in piloted closed loop systems [31].

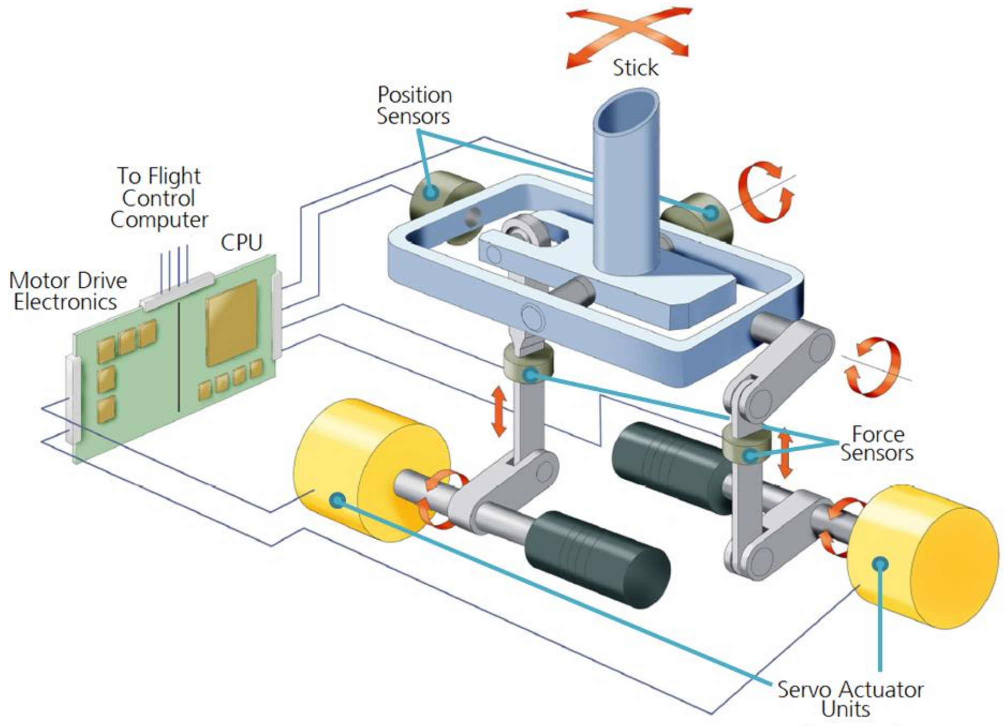

Figure 2.1: Schematics of internal assembly for a two axes active sidestick [4]

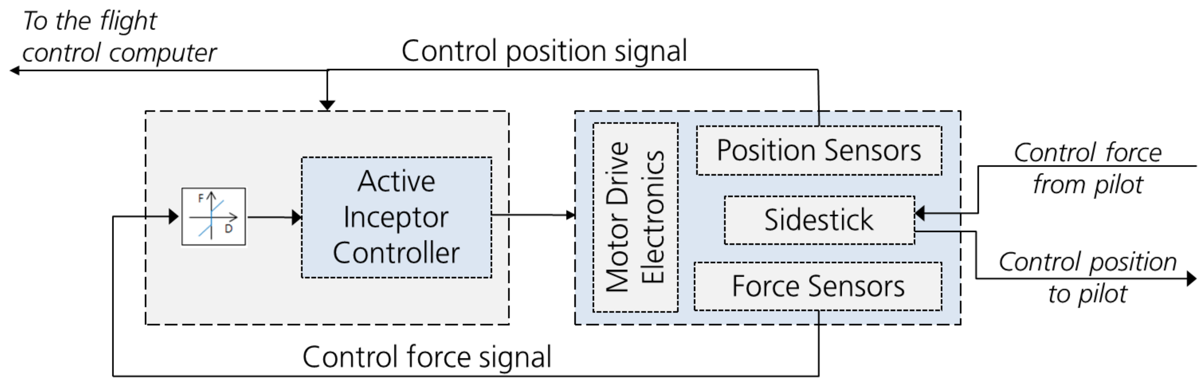

Figure 2.2: Active inceptor functional block diagram showing feedback loops - adapted from [4]

In order to have an overview of the active inceptor system architecture, the information flow is depicted in Figure 2.3. In this design approach, as suggested by Jeram [32], the active inceptor system is an independent control system nested within the overall closed loop. The pilot generates a force and the internal control scheme following the inceptor force-deflection algorithm moves the stick to the position where the force is prescribed. Position signals are transmitted to the flight control computer via a digital bus, and are used as helicopter control input to the actuators of the control surfaces [33]. The feedback of the helicopter dynamics is provided to all elements of the architecture, allowing the development of specific logics based on flight data.

The active inceptor system may modify various parameters in real time[1], such as force-deflection curve, natural frequency, and damping ratio. Thus, the changes in the force control mechanical characteristics can tailor the behavior of the inceptors to assist the pilots. Not only the traditional spring-mass-damper forces are emulated, but also a wide range of additional tactile cues can be implemented [34]. The indication of specific events to the pilots, e.g., mode engagements or impending envelope limits [7], can be achieved by harmonizing force signals in active inceptors. The tactile cues in real-time may include variable spring gradients, detents (Figure 2.4a), gates, ramps, soft stops (Figure 2.4b), stick shakes (Figure 2.4c), force breakouts, and other features.

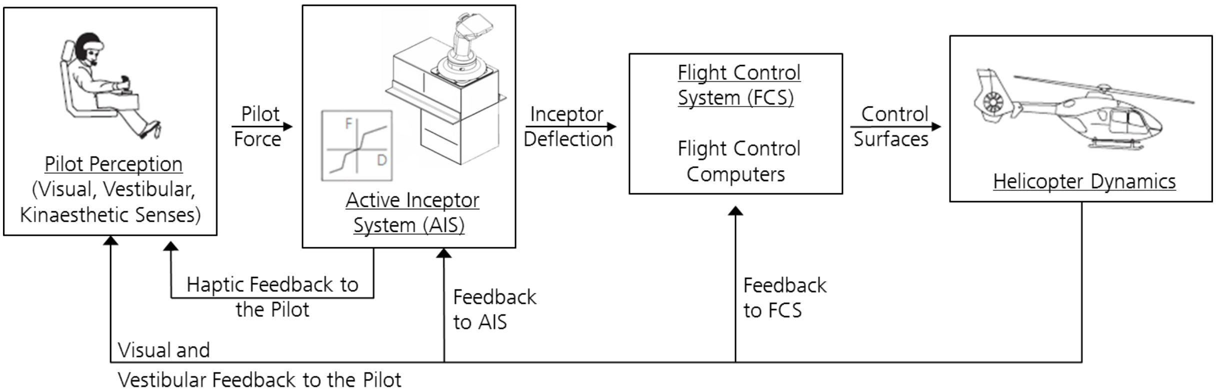

Figure 2.3: Pilot-inceptor-helicopter loop - modified from [32]

Additional usual capabilities of active inceptors are listed below [8].

- Emulation of the dynamics of a second or higher order mechanical system by programming the desired natural frequency and damping ratio of each stick axis
- Programmable characteristics of static and dynamic friction
- Variable range of control travel (end stop - Figure 2.4b)
- Adaptable force and position scale factor for calibration purposes
- Emulation of the master force-deflection curve gradient
- Back-drive of the commands generated by the auto-pilot systems

The operating concept of active inceptors can be applied to the primary pitch-roll control system (so-called cyclic lever in helicopters), rudder pedals, and heave controls (collective lever).

[1] The ability of the active inceptor system to process data in real time is influenced by the integration parameters, which is not addressed by the present work.

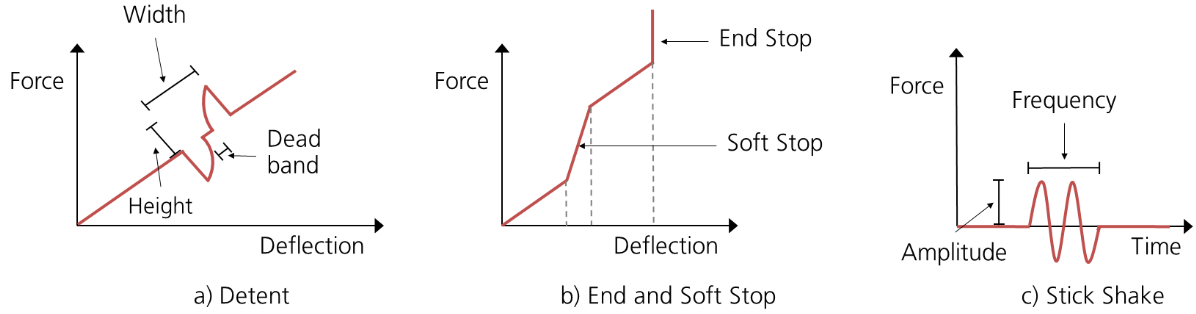

Figure 2.4: Examples of tactile cues programmed by active inceptors

2.2 The Sidestick Choice for Active Inceptors

The lack of mechanical linkages opens up the possibility to replace the traditional center control inceptors with small-size laterally positioned grip, so-called sidesticks. The ability to control the helicopter by electric sensors contributes to the reduction of various constrains in the design of a control stick. For instance, the sidestick choice offers better visibility of the instrument panel and displays, comfortable pilot’s posture by having the pilot sit in an upright position, and enhanced cockpit design flexibility [35], [36]. Therefore, the main advantage of sidesticks is better ergonomics of pilot workstation in comparison to the conventional inceptors.

Comparative studies between large-displacement conventional inceptors and short displacement sidesticks were conducted to investigate the impact of each active inceptor type for helicopters. Whalley *et al.* [37] examined methods of helping pilots to observe flight envelope limits while conducting precise and demanding evaluation tasks. Both active control types (conventional and sidesticks) showed nearly equivalent performance to identify torque and rotor stall limits with active tactile cues. A major conclusion pointed out that the active sidesticks yielded favorable pilot commentary regarding posture, feel characteristics, and controllability. Figure 2.5 shows the active sidesticks used for the left and right side in the mentioned evaluation.

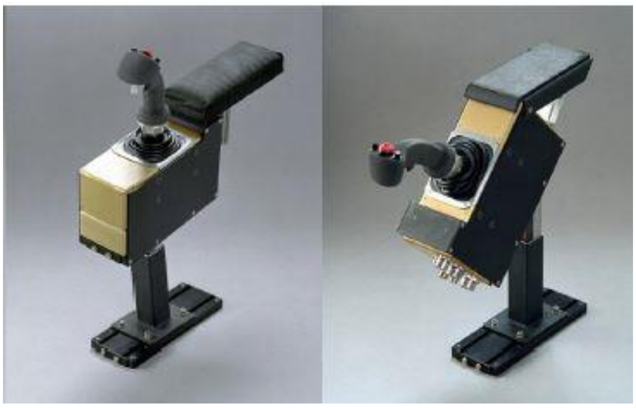

Figure 2.5: Active sidesticks as cyclic (left picture) and collective lever (right picture) [37]

In a cooperative research by the US Army and DLR, several in-flight experiments were conducted using an active center cyclic stick in the Rotorcraft Aircrew Systems Concepts Airborne Laboratory (RASCAL) JUH-60A and an active cyclic sidestick in the German Active Control Technology/Flying Helicopter Simulator (ACT/FHS) [38], [39]. The aim was to study the influence of the dynamic characteristics (natural frequency and damping) of the cyclic stick on the overall handling qualities. The preferred stick characteristics varied considerably for the different inceptors. The sidestick generally requires lower damping ratios, which may be attributable to the wrist action necessary for controlling the sidestick as opposed to the arm action for controlling a center stick. The authors concluded that the cyclic force-feel characteristics have a significant impact on pilot control dynamics and should be closely investigated.

Following the mentioned findings, the feel-control characteristics of the active sidesticks used in the present work is thoroughly examined, as will be shown in the Chapter 4.

2.3 Coupled Active Sidesticks

The inherent nature of an active inceptor design provides the ability to electrically couple two active control sticks such that they act in unison as if mechanically linked [4]. Figure 2.6 shows the pilot-inceptor-aircraft loop including a simplified signal flow used to couple the active sidesticks.

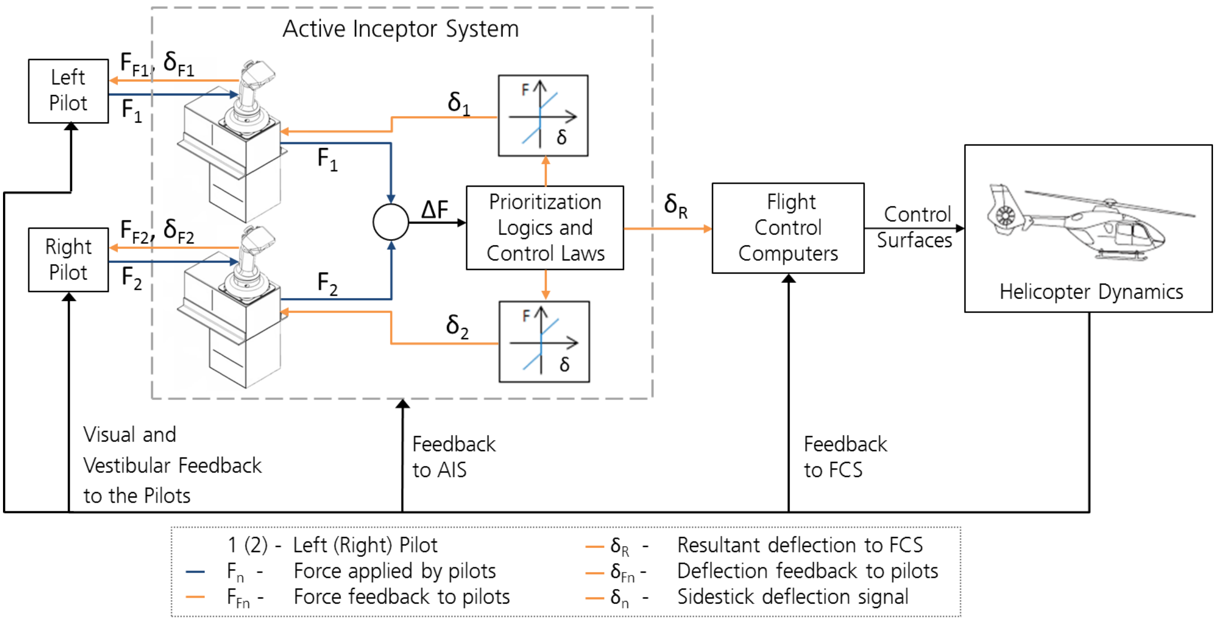

Figure 2.6: Pilot-inceptor-aircraft loop including the active sidestick coupling

The forces applied by pilots are measured by the force sensors and sent to a computer within the AIS, here represented by the prioritization logics block. The force-deflection characteristics (graphs of $Fx\delta$) are adjusted according to the internal control laws, the forces on inceptors, and flight data from the helicopter dynamics. For simplification, the information sent back to the sidestick units are indicated by the inceptor deflection (δ) in Figure 2.6. However, the active modifications can include not only the inceptor position, but also all static and dynamic parameters, like natural frequency, damping ratio, stiffness, friction and others. Pilots can feel the corresponding deflection of the sticks through the servo motor in each axis as a function of either the applied forces from the opposite sidestick, or the supplementary tactile cues generated by the AIS.

The inceptor coupling is achieved by specifying logics via electronical signal to transmit the forces of one sidestick to the other. This architecture can be programmed to provide the emulation of the mechanical cross-cabin linkage, the so-called virtual rigid coupling. No real shaft between the sidestick units is implemented, although they can behave as if rigidly connected. The virtual rigid concept is the result of equal sidestick deflection output by the prioritization logics block ($\delta_1 = \delta_2$). Since both sidesticks are in the same position with respect to their neutral points, the input signal to the flight control computers (δ_R) will correspond to the actual position of the sidesticks (δ_{F1} and δ_{F2}).

Hegg *et al.* [40] refer to the virtual rigid coupling as an beneficial aspect in case of force fight. In this condition, both pilots apply inputs in opposite directions in the same axis. The emulation of the mechanically linked inceptors provides displacement and force feedback to both pilots; therefore, the dual input may last just for brief seconds before the pilots' recognition.

It should be highlighted that the forces felt by pilots are delimited by several parameters, including the servo motor limit. If this limit is reached during a force fight between the pilots, the sticks will then move in opposite directions until one pilot's force is relaxed below the capability of the servo motor.

2.3.1 Rationale for the Virtual Rigid Coupling Design

Virtual Rigid vs. Non-Rigid Coupling Concepts

The virtual rigid coupling transmits the force feedback to the pilots at the grip (F_{Fn}), which corresponds to the resultant position input (δ_R) that is sent to the FCC (Figure 2.6).

In the case of the non-rigid coupling, the externally applied manual force input is transmitted to the FCC, which modulates the position of the sidesticks [41]. In brief, the sidesticks are programmed to basically track the position of each other. The force to deflect the grips is just the necessary to modify their position. Thus, in case of force fight, the necessary force to overcome the normal force-deflection gradient is enough to trigger off mismatched position of the sidesticks.

Specific flight control laws must be implemented to handle the resulting discrepancy of the input signals, because the relation of force and the deflection was modified by the simultaneous forces on control. Mühlratzer [41] indicates that, in the non-rigid coupling, the divergence between the sidestick position and the helicopter behavior after the processed inputs results in spongy control feeling to the pilots. Uehara [8] highlights that the mismatch between the positions of the sidesticks can be relatively frequent in the non-rigid coupling. Since there is no force transmission, even a small force applied by the PM on the sidestick when trying to follow the PF's control inputs can lead to a mismatch. Therefore, the frequent mismatches of the sidesticks are likely to occur, and the algebraic sum of the signals from the two sidesticks as the input to the FCC is not an appropriate solution [8]. Moreover, the command of a priority pushbutton in non-rigid configuration with sidestick in mismatched positions will trigger an abrupt change of the input signal to the FCC, requiring additional functions to lessen the problem [8].

The rationale to implement the virtual rigid coupling is the possibility to provide both force and position feedback to the pilots, whereas the non-rigid coupling can only give information about the sidestick position when just one pilot is applying input.

The Mechanical vs. Electronic Coupling Solution

The mechanical cross-cabin coupling is the current design in almost all non-FBW helicopters flying in the world. In the case of FBW helicopters, however, it seems to be at least a suboptimal approach when compared to the coupling via active sidesticks, as explained below.

Dual-pilot cockpits featuring the electronic coupling can benefit from the additional feel and cueing capabilities without the life cost penalties of fairly complex mechanical linkages. In terms of design, the mechanical approach has to compensate potential side effects as friction, backlash and inertia [6]. In comparison with the electronic means, the mechanical links provide the coupling at the expense of higher weight, vulnerability, and maintenance complexity [41], [5].

The flexibility of the electronic coupling systems provides the ability to decouple inceptor via the software that controls the sidesticks [8], which is illustrated as the prioritization block in Figure 2.6. Hence, the electronic coupling allows the pilots to decouple the sticks if required without additional mechanisms. On the other hand, the mechanical design needs a shear pin to be broken to disconnect the sticks [5]. This mechanical decoupling solution adds failure critical points, and its production can require additional safety levels to overcome the hazards of the separation system [6].

If one sidestick is electronically disabled, the signal from this sidestick is cancelled by the active inceptor system. In the event of jam of one sidestick, the helicopter can be controllable if the decoupling system is activated. The decoupling would be also useful in failures to isolate the malfunctioned sidestick unit and to avoid the impact on other active stick.

2.4 Helicopters featuring Active Inceptors

Currently under development, the CH-53K is expected to be the first production helicopter featuring electronic coupled active sidesticks in both pilot stations for cyclic and collective levers [42]. The CH-53K King Stallion is a triple-engine, 38-ton military cargo helicopter, as illustrated in Figure 2.7. This rotorcraft is part of the US Marine Corps (USMC) heavy lift program, including triplex redundant flight control computers and active inceptor system to replace its helicopter predecessors (CH-53A, CH-53D/G, and CH-53E). The active sidesticks features to be implemented have not been made public yet.

Figure 2.7: CH-53K King Stallion external view (left) and active sidesticks (right) [42]

The architecture of the FCS of the CH-53K is based on prior programs developed by the Sikorsky manufacturer. The main example is the medium-lift utility UH-60M Upgrade Black Hawk, which consists of a pair of electronically coupled center cyclic and collective inceptors at each pilot station with passive directional control pedals [43]. The M-model Upgrade Program is the FBW version of the twin-engine, 10-ton Black Hawk helicopter, but its serial production has not been confirmed over the years.

Remarkable contributions to the development of the active sidesticks were provided by the in-flight simulators, i.e., highly modified helicopter for research and development (R&D) purposes [44]. These helicopters represent a sophisticated research test bed for active FCS. The main in-flight simulators used as research tools for active technology are listed below.

- Advanced Systems Research Aircraft (ASRA), operated by National Research Council Canada (NRC) [45]
- ACT/FHS, operated by DLR [34], [39]
- RASCAL, operated by the US Army and NASA [43], [46]
- Advanced Technology Institute of Commuter (ATIC) BK117 Experimental, operated by Kawasaki Heavy Industries [35], [47]

The major technological challenge of the electronic coupling in active sidesticks can be partly circumvented by the adoption of mechanical linkages between the cross-cabin inceptors. This is the flight control design in the CH-148 Cyclone. Historically also mentioned as S-92F or H-92, it is a substantially modified derivative of the commercial S-92A [48]. The 13-ton, twin-engine military helicopter was developed for the Canadian Forces. Only the collective lever is a mechanically interconnected active inceptor. The FBW flight controls also include two sets of passive pedal modules for yaw axis and two passive small displacement center cyclic levers for pitch and roll axes [49].

It is noteworthy that no fly-by-wire helicopter featuring active coupled sidesticks has obtained civil certification. The aforementioned helicopters are prototypes or military types. Bell 525 Relentless can be the first commercial helicopter to incorporate full authority FBW digital flight controls in near future. The 9 ton rotorcraft will be equipped with mechanically interconnected pilot-copilot sidesticks and pedals, as presented in Figure 2.8 [50]. The manufacturer indicated several benefits related to active technology, such as automatic bank angle and hover holds, high rate of descent protections, autorotation[2] entry assist, and collective tactile cueing [51]. But no reference of a mechanism for cross-cabin sidesticks decoupling was specified so far.

Overall, the decision to implement electronic or mechanically interconnect sidesticks is still a matter of debate. FBW helicopters featuring electronic inceptor coupling, as CH-53K, did not achieve initial operating capability and the complete understanding of this design in service is still not possible. Thus, part of the effort of the present thesis is dedicated to investigate how future dual pilot FBW helicopters could benefit from the incorporation of electronically coupled active sidesticks.

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[2] Autorotation is a state of flight in which the main rotor system of a helicopter turns by the action of air moving up through the rotor, rather than engine power driving the rotor. The condition is routinely practiced by pilots in reference to the safe helicopter landing in event of complete engine failure.

Figure 2.8: Bell 525 mechanically linked flight controls (left) and flight deck (right) [50]

2.5 Literature Review about Active Coupled Inceptors

The literature review is divided into two parts. The first subsection (2.5.1) presents an overview of the studies regarding the active inceptor technology in helicopters. The aim is to highlight the relevance of the force feedback as a channel of communication, generally in conditions of high workload.

The second subsection (2.5.2) addresses the works focused specifically in the active inceptor coupling. The goal is to describe the scientific contributions to the understanding of the human-machine interaction in the particular case that active force feedback is generated to provide inceptor cross-cabin coupling.

2.5.1 Review of Active Inceptor Technology in Helicopters

Tactile feedback via the active inceptor system became the center of research attention, due to the potential ability to assist pilots in high workload conditions. A common goal is to maximize the performance and to reduce pilot workload to monitor the flight envelope limits, which is likely to increase situational awareness [52]. The active functions are discussed according to the inceptor type in which they are programmed (collective or cyclic lever).

Cues for Active Collective Inceptor

Since power demand is predominantly associated with pilot collective inputs, tactile cues can be encoded on the active collective inceptor as a torque exceedance protection [4]. As indicated by Müllhäuser and Leißling [53], the torque limit is an ideal candidate for tactile cue, due to its slow dynamics and nearly proportional dependence of the collective deflection. Consequently, several researchers investigated methodologies for engine torque prediction algorithm to calculating maximum collective control deflection based on generally proportional quasi-steady torque [54], [55]. Demonstrated benefits related to the torque protection are reduction of limit exceedances [34] and reduction in pilot workload [53], either in flight and simulator.

Sahasrabudhe *et al.* [55] used a neural network and linear model based algorithms to predict approaching envelope limits including transmission torque, rotor RPM, engine torque, and the optimal RPM following an OEI (one-engine inoperative) emergency. The results of the piloted simulation showed that tactile feedback applied on collective led to improvements in task accuracy for aggressive maneuvers. Moreover, multiple limits can be cued through the collective without confusion, but only through the judicious use of different cues.

The active cues on collective inceptors can also assist pilots to increase the task performance by providing augmented force feedback to detect optimum inceptor position for a given task. In simulated flight tests, tactile cues functions using active collective inceptors showed improvements in the execution of the autorotation phases [56], in prevention of vertical speed limits [57] and in avoidance of vortex ring state[3] (VRS) domain [52], [58].

A thoroughly comparative study was performed by Whalley and Achache [59] to verify the efficiency of the tactile cues to warn pilots through recommended collective deflections. The comparison in piloted simulation included four types of cues: collective stick force feedback, visual symbology (head-up display - HUD), aural tones, and voice warnings. The results are meaningful because the tasks were considered as high workload conditions, as 180° turning autorotation and vertical mask-unmask. The tactile cues in the collective lever were described as the most immediate and strongest cue [59]. The active feedback was also indicated as very effective in drawing attention, similarly to an instructor pilot providing assistance [59]. The comparison indicated significant benefits to the task performance in the case of tactile cues via the inceptors. But the combination of tactile and visual cues led to better results for the evaluated maneuvers [59].

In summary, the tactile cues in collective lever were helpful because pilot could look more outside and less to the instrument panel to monitor the parameters.

[3] Vortex Ring State is an aerodynamic condition that may arise when the helicopter descents in its own downwash, causing severe loss of lift.

Cues for Active Cyclic Inceptor

Abildgaard and von Grünhagen [60] developed tactile cueing functions in the ACT/FHS for a g-load limitation in the longitudinal cyclic axis and for a standard rate IFR-turn in the lateral cyclic axis. The latter tactile function was workload rated and showed noteworthy reductions and better situational awareness. It worked as flight guidance function with lateral soft-stops [60]. The active g-load limitation demonstrated correct function, but control law optimization appeared to be necessary.

Furthermore, an envelope protection function for the rotor mast bending moment was tested in the simulator [60]. A softstop on the cyclic stick indicated to the pilot the control limits corresponding to mast bending moment limits. The tactile cue was considered helpful, because the pilot looked mainly outside the cabin and dedicated more attention to control the helicopter instead of monitoring the instruments [34], [60].

Einthoven *et al.* [61] developed tactile cueing algorithms for a three axis active sidestick controller. In a simulation environment, tactile cues provided additional information about the following limits: control margin, mast moment and load factor in longitudinal cyclic axis; bank angle in lateral cyclic axis; and tail-rotor gearbox torque in directional cyclic axis. The research concluded that tactile cueing allowed the pilot to reach the limits more aggressively and to focus out of the window, which afforded additional pilot situational awareness. Another leading outcome was the harmonization of tactile cues for multiple limits.

Similar results were pointed out by Whalley *et al.* [37]. The simulation trials used a UH-60 model in the NASA Ames Vertical Motion Simulator (VMS). They analyzed the ability of the system to help the pilot to observe flight envelope limits while conducting precise evaluation tasks. The tactile cueing was implemented as helicopter flight envelope protection to represent limits of blade stall and mast bending moment in active cyclic sidestick. The major findings indicate that tactile cues can significantly reduce the time required to reach the envelope limit, reduce exceedances, and improve pilot opinion [37]. Tactile cueing enabled the pilots to easily track rotor stall limits while performing an aggressive turning task with their attention focused entirely outside the cockpit.

In short, tactile cueing has proven to be an effective method of increasing situational awareness [62], especially during demanding situations, and can reduce pilot workload for increased operational safety.

2.5.2 Review of Active Inceptor Coupling

Although considerable attention is being dedicated to optimize the tactile cues for the PF, there remains a paucity of evidence on how active technology can provide appropriate inceptor cross-cabin coupling in helicopters. Therefore, the interactions of PF-PM using this technology in rotorcraft remain unclear.

Review of Active Coupled Inceptor in Airplanes

The most notable works about active coupled sidesticks focused on the possibility to implement inceptor coupling in A320 aircraft. There is a clear underlying motivation for these investigations. In the late eighties, Airbus decided to equip the new FBW model with passive uncouple sidesticks, raising question about the impact of this design to the situation awareness [6].

Shortly before the A320 certification, Summers *et al.* [11] have foreseen the discussion regarding the lack of inceptor coupling. The study compared an active system that emulates mechanical coupling and passive uncoupled sidestick in a fixed based simulator using an A320 model. They concluded that, in the event of overriding maneuvers performed by the PM without prior information, the response time of the PF was lower with the coupled sidesticks [11]. The pilots preferred coupled sidesticks because they could obtain force feedback through the control stick and the forces communicated a sense of urgency. A comparison of takeover control methods from the autopilot was performed, either by applying force on the stick or by pushbutton [11]. Pilots stated that the force override maneuver was a natural reaction, therefore the preferred option. However, a full discussion of decoupling methods in active inceptors lies beyond the scope of this study, since the decoupling was only available to passive uncoupled sidesticks during the dual pilot tests.

The response time of the PF due to the interference of the PM was again investigated in simulator for the A320, this time by Zaichik *et al.* [10]. While one pilot flew a landing approach, the other pilot interfered by starting a go-around through the priority button in case of uncoupled sidesticks or by merely overriding control in case of coupled sidesticks. The pilot continued the landing approach as long as 10 seconds after the interference using the uncoupled sidesticks, relying only on the aircraft reaction [10]. The response time to recognize the other pilot interference decreased to two seconds in the coupled configuration [10]. Although the results confirmed the previous conclusions, the relevance of this investigation is the quantification of the PF's response time.

Uehara [8] also investigated the consequences of active coupled sidesticks in A320 aircraft. The novelty of his work was the examination of the situation awareness of the PM, instead of the PF. In the approach and landing scenario, the results indicate that the coupling is useful for the PM to perceive the PF's control inputs and to anticipate the airplane dynamic behavior. In general, the coupling was considered useful for the decision to takeover control [8]. In the cruise scenario, the coupling was considered extremely useful to improve the PM's awareness during the event of a stall [8]. Nonetheless, due to practical constraints, this research cannot provide a comprehensive crew interaction, since the PF actions was recorded and only the PM was present in the cabin of the simulator for the evaluation, which is not a very representative scenario of the real operation. Furthermore, the research indicates improvements in pilot awareness and pilot workload without a validated method to quantify the impact of the inceptor coupling.

Due to the operational differences between fixed wing and rotary wing aircraft, some results described in this subsection are not fully applicable to the helicopter realm. However, the relevance of the findings forms a valuable theoretical framework to the present thesis.

Review of Active Coupled Inceptor in Rotorcraft

The only known work towards rotorcraft is a DLR fixed base simulator research by Burgmair *et al.* [20] that verified the use of active inceptors in tiltrotors. The dual pilot trials were focused on the procedures to transfer, prioritize and limit control of two electronically coupled inceptors. But the position and force synchronization of the two cyclic sidesticks was judged as insufficient to the flight. The inceptors were manufactured by different companies and the performance variations could not be compensated. Due to a time lag of 150 ms between the sidesticks, just a maximum bandwidth of about 3 Hz could be reached. The study suggests that the usefulness of an inceptor decoupling method should be investigated for flight training, although it was not able to assess the effectiveness of electronic linked inceptors. Moreover, they concluded that the same set of sidesticks, including the same specifications, should be selected in case of dual pilot cockpit. As a result, the present work used identical set of active inceptors in both control station inside the helicopter cabin, as will be presented in Chapter 4.

The scarcity of studies dedicated to rotary wings indicates a scientific gap which is explored in this thesis. Practically all main helicopters in service are equipped with physically interconnected inceptors, as opposed to the Airbus airplane family, which might be the reason for the research shortage. If the lack of inceptor cross-cabin coupling is not a current problem in helicopters, the imminent introduction of active inceptor brings about new inquiries, such as the capability of the new system to provide equivalent situation awareness and novel pilot assistance functions to takeover control. The present thesis is dedicated to answers these new inquiries.

2.6 Concluding Remarks

The main topics discussed in this chapter are:

- The active inceptor system provides the ability to modify in real time a wide range of parameters related to the force control mechanical characteristics, which can be programmed to assist pilots during the flight.
- The benefits of the sidestick design are associated to improved ergonomics of pilot station. However, this design requires an investigation of the force-feel characteristics, which can have a significant impact on pilot control dynamics.
- The inherent programmable nature of the active inceptors enables the emulation of the mechanical linkage through the electronic coupling of two active control sticks.
- Mismatches of the sticks' positions occur if both pilots apply inputs in the non-virtual rigid coupling, because there is no force transmission, only deflection. Therefore, this work opted to implement the virtual rigid concept, due to the possibility to provide both force and position feedback to the pilots, even in case of dual input.
- The flexibility of the electronic coupling systems allows the inceptor decoupling via the control software. This feature can be useful in case of interference on control, sidestick jam and control system failure.
- There remains a paucity of evidence on how active technology can provide appropriate inceptor cross-cabin coupling in helicopters. The research shortage can be largely attributed to the fact that the lack of inceptor cross-cabin coupling is not a current problem in helicopters, since almost all helicopters in service are featuring physically interconnected inceptors.
- The imminent introduction of active inceptor brings about new inquiries, such as the capability of the new system to provide equivalent situation awareness and novel pilot assistance functions to takeover control.

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3 Safety Aspects of the Inceptor Coupling in Dual Pilot Operation

Whereas the previous chapter of this thesis addressed the literature related to active inceptor systems, this chapter discusses the importance of coupling the inceptors within a flight cabin. The first section presents the force feedback significance for pilots as an operator of haptic devices. The section 3.2 analyzes the influence of the inceptor coupling in dual pilot operation, highlighting the importance of this design to flight training. Lastly, the section 3.3 describes and discusses a few flight accidents, in which the inceptor coupling was present as a decisive contributing factor to the occurrence of these events.

For consistency, the term FI is interchangeably used to indicate the PM, as the trainee pilot refers to the PF. However, since some references used the broader term PM and PF, these acronyms are still included to keep the source wording.

3.1 Force Feedback Significance

In some conditions, the force feedback from the inceptor coupling can work as an additional channel of communication. The force feedback can be useful to mitigate the limitation of humans to process the information, because the overuse of visual and auditory interfaces may create points of limited processing capacity for pilots [30], which are explained below.

The current understanding of human mental processing suggests that information is perceived through multiple sensory processors [63, p. 1059]. The information is perceptually encoded by the sensory memory, which converts it to a usable mental form [64], [65], as shown in Figure 3.1 [66]. However, the identification and recognition of the stimulus depends on the form of information, since there may be different sensory memory system for each of the human senses, including visual, auditory, haptic, olfactory, and gustatory.

In the case of the visual sensory memory, when the eyes detect an image and no attention is dedicated to it, the information is not transferred to the working memory[1]. Then, the iconic sensory memory modality is fleeting, decaying completely, on average, in about 200 ms [68], [69]. Aural, or echoic sensory memory, is a bit more persistent, with the "internal echo" lasting an average of about 1.5 seconds [69], [70]. The haptic sensory memory has a decay rate between 2 and 8 s [71], [72]. Little is known about olfactory and gustatory sensory memories.

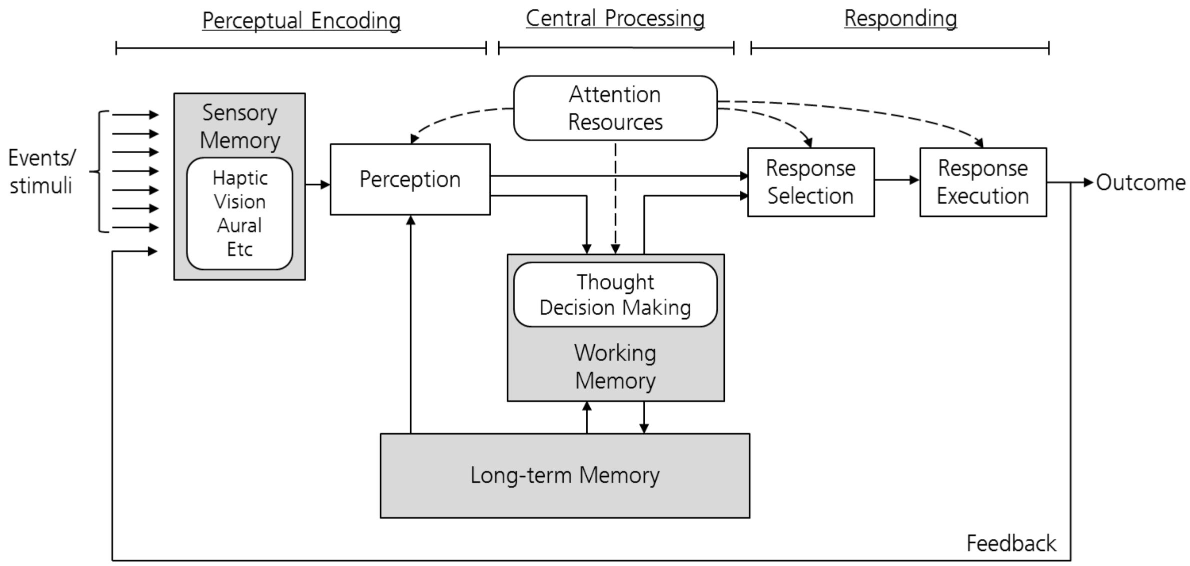

Figure 3.1: Model of human information processing - adapted from [66, p. 147]

Pilots flying in demanding conditions may have to prioritize the incoming information, so not all cues will have enough attention directed to be transferred to the working memory for the cognition process. That is why human beings tend to block out some sensory input during moments of high workload. The haptic input channel is generally held open longer than visual and aural perception, and pilots can benefit from the additional time to recognize the information.

Moreover, even when attention is dedicated by the pilot to send the information from the perceptual processor (via eyes and ears) to the cognitive processor, there is a limited capacity to this end. Considerable amount of information is already displayed to the pilot in the flight cabin, and in the external environment. Endsley [73] suggests that overburden of one channel is not appropriate if simultaneous information processing from several sources is required. Therefore, it is highly desirable to use other human

[1] According to Wickens and Carswell [67, p. 133], working memory or short-term memory refers to the number of ideas, sounds, or images that we can maintain and manipulate mentally at any point in time. Working memory is of limited capacity and heavily demanding of attention in its operation [66, p. 119]. It is responsible to store the information required for parallel tasks.

senses to convey information, as the force-feedback of inceptors. The haptic channel is a method to enhance sensory perception by exploiting multiple sensory channels for increased input capacity.

A distinguishing feature of haptic sense is the bidirectional flow of information, which is not the case of the visual and vestibular perception [9]. The forces on controls inform pilots through his muscles and joints, which will execute the response during the human information-processing. Moreover, the cross-cockpit coupling stimulates fast reflexive motor responses that do not require high cognitive demands of the operator [74], [75]. These aspects of the force-feedback carry considerable weight in the interactions between the pilots during the flights, as will be addressed in the next section.

3.2 The Situation Awareness Problem

The cross-cockpit coupling of flight control inceptors is a communication link between two pilots. When the control deflection in one stick is not mirrored in the inceptor of the other pilot, the crew may have his situation awareness affected [13]. In this case, pilots can no longer employ the inceptor to convey information of the future aircraft states.

The absence of inceptor cross-cabin coupling, or the inappropriateness in its implementation, may adversely affect the awareness of the pilots in at least two tasks. Considering the interaction of pilots under the FI's point of view, the tasks are described in the Table 3.1.

Table 3.1: Analysis of tasks influenced by inceptor cross-cabin coupling

#	Task	Method	Goal
1	Monitor the helicopter states	Follow through technique	- Increase flight predictability and situation awareness
2	Monitor the inputs of the trainee pilot	Follow through technique	- Monitor trainee pilot's performance to detect inappropriate inputs or to avoid unsafe conditions

The first task involves the ability to monitor the flight condition and to predict the future states of the helicopter. The FI can increase his awareness by resting hands and feet lightly on controls, which is also known as follow through technique [76]. While the first task is associated to the flight predictability as a whole, the second is directly related to the supervision of the trainee pilot. The force feedback allows the FI to check the trainee pilot's performance by following closely the inceptors.

The responsibility of the FI to accomplish the tasks of the Table 3.1 is recognized by the aeronautical community, herein referred to as PM. For instance, a Safety Alert for Operators (SAFO) [77] issued by the Federal Aviation Administration (FAA) in 2015 recommends that each operator should explicitly define the roles of the PF and PM, including the following:

- The PF is responsible for managing and the PM is responsible for monitoring the current and projected flight path and energy of the aircraft at all times
- The PM supports the PF at all times, staying abreast of aircraft state
- The PM monitors the aircraft and system states, calls out any perceived or potential deviations from the intended flight path, and intervenes if necessary

According to the Civil Aviation Authority (CAA) from UK, both pilots are "responsible for maintaining their own big picture gained through cross checking each other's actions" [78]. The aviation agency highlights that the monitoring skills are important to maintain high levels of situation awareness, otherwise the identification of deviations and hazardous external environment may be impaired. Hence, pilots are instructed to continuously cross-check the actions of the other crew member.

The inceptor coupling can be particularly useful in flight training to increase the FI's awareness about the actions of the trainee pilot. The instructor habitually detects the trainee's inputs via direct kinesthetic feedback to raise the understanding of the actions in the cabin as part of the cockpit error management.

Consistent with the tasks described in Table 3.1, Taylor [79] indicated that the position and movement of the inceptors convey information from one pilot to the other concerning status of the aircraft and the handling pilot's intentions. The author suggested that the physical linkage across the cabin is a line of communication between two pilots without the need of either verbal or visual information transfer. Likewise, Field and Harris [13] also infer that inceptor cross-cockpit coupling is a communication link to convey information of both current and anticipatory aircraft state. However, the authors listed in this paragraph did not provide empirical validation to determine the likely variation in situation awareness attributable to the control inceptor configuration.

Next subsection defines the term situation awareness and correlates its definition with dual-pilot flights.

Situation Awareness: Definition and Implications in Dual Pilot Flights

The inceptor coupling can increase situation awareness by validating the information the pilots gain about the world (together with the aircraft dynamics) and predicting near future of the helicopter through the force feedback.

Situation awareness (SA) is recognized as a critical foundation for good decision making in complex and dynamic environments such as aviation [79]. As depicted in Figure 3.2, SA involves three levels by the definition of Endsley [80]. The main characteristic of the first level is the perception of critical factors in the environment. The second level relates to comprehend the meaning of those factors, particularly when integrated together in relation to the aircrew's goals. At the highest level, there is the understanding of what will happen with the system in the near future, i.e., projection or prediction.

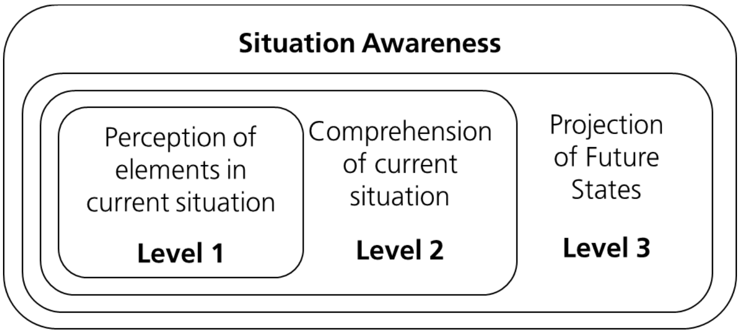

Figure 3.2: Three levels of the situation awareness [80]

The perception at level 1 traces directly to issues of selective attention and attentional capture. Indeed, Jones and Endsley [18] found that a majority of aircraft accidents attributable to loss of SA were related to breakdowns at this first stage. Wickens and Carswell [67, p. 135] suggest that humans can easily fail to notice significant changes in dynamic systems. Therefore, failures at level 1 typically require interventions involving designs to increase the user's attention.

To this end, the perception of the inputs, provided by the force-feedback in the active inceptor, can influence the mental model of pilots about the state of the flight. The ability to predict the future states of the helicopter flight is crucial for the instructor pilot, but it depends on a deeper comprehension of the relation between the inputs applied on inceptor and the helicopter response. It is especially significant in time-critical situations, as near obstacle flights.

Parasuraman *et al.* [81] stated that mental workload and SA are among a small number of human cognition and performance constructs that have the highly useful properties of being both predictive of performance in complex human–machine systems and diagnostic of the operator's cognitive state. Consequently, measures of both mental workload and SA can provide insight to designers seeking to improve the performance of pilots using inceptor couplings in dual pilot helicopters.

Overall, this section asserts that the inceptor coupling plays an important role for the situational awareness of the crew, in particular for the FI. Moreover, this reasoning leads to the understanding that the active coupled sidesticks should demonstrate the ability to provide situational awareness, enabling the FIs to comply their monitoring responsibility.

An additional task of the FI is the need to intervene on control, if there is an imminent safety risk. The interventions will be discussed in detail in the following section, which analyses the takeover control problem.

3.3 The Takeover Control Problem

The PM (and therefore the FI) must timely intervene in the event of a deviation or by safety reasons, as defined by the CAA [78]. The type of intervention varies corresponding to the level of safety risk. For instance, the inaccurate path of the helicopter could motivate the FI to verbally recommend a correction in the helicopter heading. A different kind of intervention is advocated in case of an imminent collision with obstacles. The FI is encouraged to takeover controls in unexpected, unforeseen or unsafe conditions [19]. In the context of the aviation, the main reasons for the FI to suddenly interfere in control can be [10]:

- Abrupt changes of aircraft attitude (FCS failures, etc.)
- Dangerous atmospheric disturbances
- Unexpected obstacles or warnings
- Pilot state dangerous changing (unexpected assault, trauma, etc.) and others

Therefore, the takeover control maneuver performed by the FI is a recommended action under conditions in which the flight safety is threatened. In these situations, the inceptor coupling allows the FI to overpower the trainee (PF), i.e., FI applies more force on inceptor than the trainee pilot to handover the control and to swap roles of the pilots.

However, the interaction of pilots during takeover control is a cause of loss of control accidents, particularly in flight training[2]. In these cases, the failure of the trainee pilot to recognize the control transfer typically caused the lack of positive exchange of controls, which triggered difficulties in the controllability of the helicopter. This problem is referred to as control interference and will be analyzed in the subsection 3.3.2. Next subsection emphasizes why the flight training is a special case for the present discussion.

[2] The National Transportation Safety Board (NTSB) defines the flight training or instruction as "flying accomplished in supervised training under the direction of an accredited flight instructor" [80]. The flight training is not limited to airmanship skills, but includes pilot judgment and decision-making practices [18].

3.3.1 Flight Training Aspects and Safety Statistics

The flight training imposes additional risks to the instructor pilots in case of takeover control. The FI must combine the responsibilities of the PM with the teaching duties. Moreover, the FI is the ultimate accountable for unsafe conditions during the flight. According to the guidelines of the FAA to the helicopter instructors [26], the main hazards are:

- *Trainee's inappropriate inputs:* The training combines the physical demands of controlling the helicopter and mental challenges of learning how to fly in environment with noise and vibration. This is a stressful scenario, where the possibility of trainee's mistake should never be underestimated. Eventually, during the control transfer, inadequate time for verbal interactions can occur. In this case, an inevitable manual overriding control must be immediately assessed, even without prior notice. Thus, there is a strict recommendation that "FIs should always guard the controls and be prepared to take control of the aircraft".
- *Misunderstanding of who is the pilot flying*. Since the helicopter instructor needs to rest the hands on controls during flight training, the action of helping the trainee can lead to misinterpretation of who actually has control of the helicopter. This condition is likely in high workload and time-critical conditions, when communication between the pilots may be affected. According to FAA, the procedure of exchange of control is the cause of numerous accidents.
- *Controls Blocked*. During the action of takeover control by the instructor, there is a response time in which the trainee is still processing what is happening. The delay can last longer in flight training, because anxious trainees can exhibit reactions inappropriate to the situation, ignoring the inputs of the instructor. Additional cases can be mentioned as following: trainee's knee unintentionally blocking the excursion of the cyclic movement, objects (water bottles, clothing and cameras) becoming lodged in the inceptors, or the trainees boot or shoe blocking anti-torque pedals.

The European Aviation Safety Agency (EASA) recommends the helicopter instructor pilots to adopt the following attitudes towards the trainees: "prompt, question, direct, or physical intervention if necessary (take control)" [82].

These additional risks of the flight training may be reflected in statistical analyses. Safety review in Europe shows that 18% of the helicopter accidents from 2007 to 2011 happened during training flights [83]. The distribution of accidents by flight phase is presented in Figure 3.3 [83]. Whilst the approach and landing phases generally represent 25% of the overall helicopter accidents; this indicator corresponds to 44% in training flight. It should be noted that more approaches and landings are usually performed in training flight compared to normal operations.

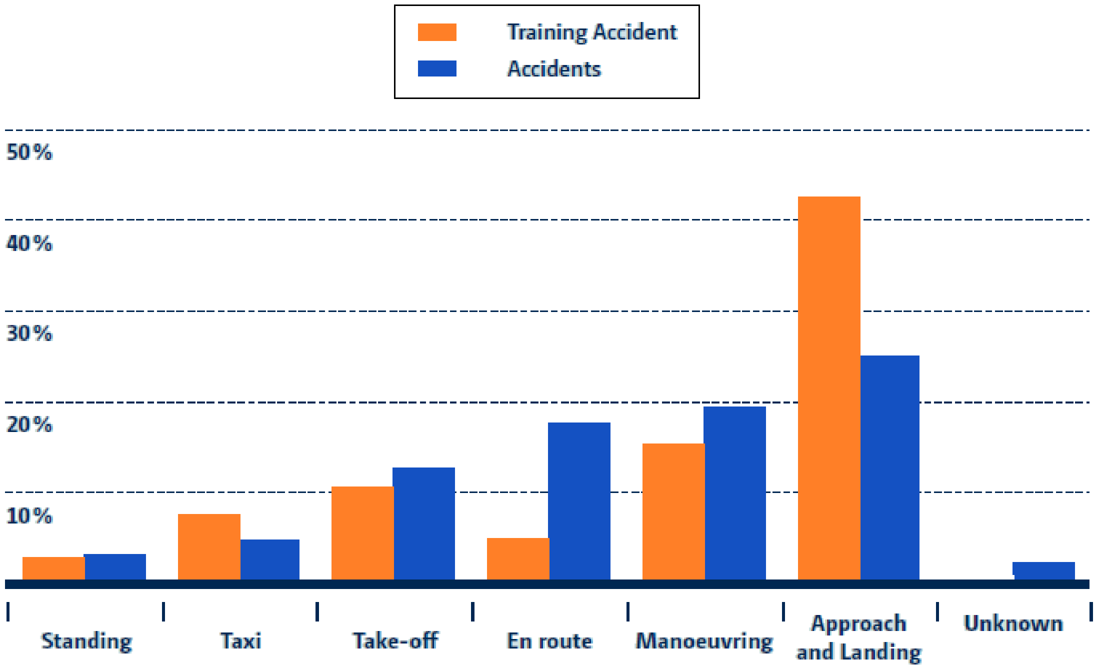

Figure 3.3: Distribution of accidents by flight phase; European helicopter accident data; flight training operations (2007 – 2011) [83]

In the US, instruction/training accounts for approximately 20% of helicopter accidents [27]. The exact percentage varies depending on the sample time. For instance, between 2001 and 2010, 21.7% of the helicopter accidents occurred in flight training which is equivalent to 363 out of 1672 accidents according to the NTSB classification [84].

The comprehensive investigation of the International Helicopter Safety Team[3] (IHST) can provide a deeper understanding of the figures presented. The safety analysis comprises helicopter accidents of the years 2000, 2001 and 2006. A total of 523 accidents of were analyzed [22]. As shown in Figure 3.4, occurrences in training are the second highest number of accidents of any industry sector, corresponding to 92 (17.6%) events.

[3] The IHST was formed in 2006 by representatives of the government and helicopter industry to address the unacceptably high long-term helicopter accident rates. The organization pursued the goal of reducing the worldwide civil and military helicopter accident rates by 80% in 10 years [85]. By the end of the 10-year milestone, the accident rate in key regions has decreased within a range of 40% to 60% [86].

The IHST also grouped the same set of accidents by *activity*, instead of the *industry sector*. The classification of *activity* was developed to further clarify what mission the helicopter was performing at the time of the accident, independently of industry segment. In this later analysis, the training flight activity is the highest accident percentage, as illustrated in Figure 3.5 [22].

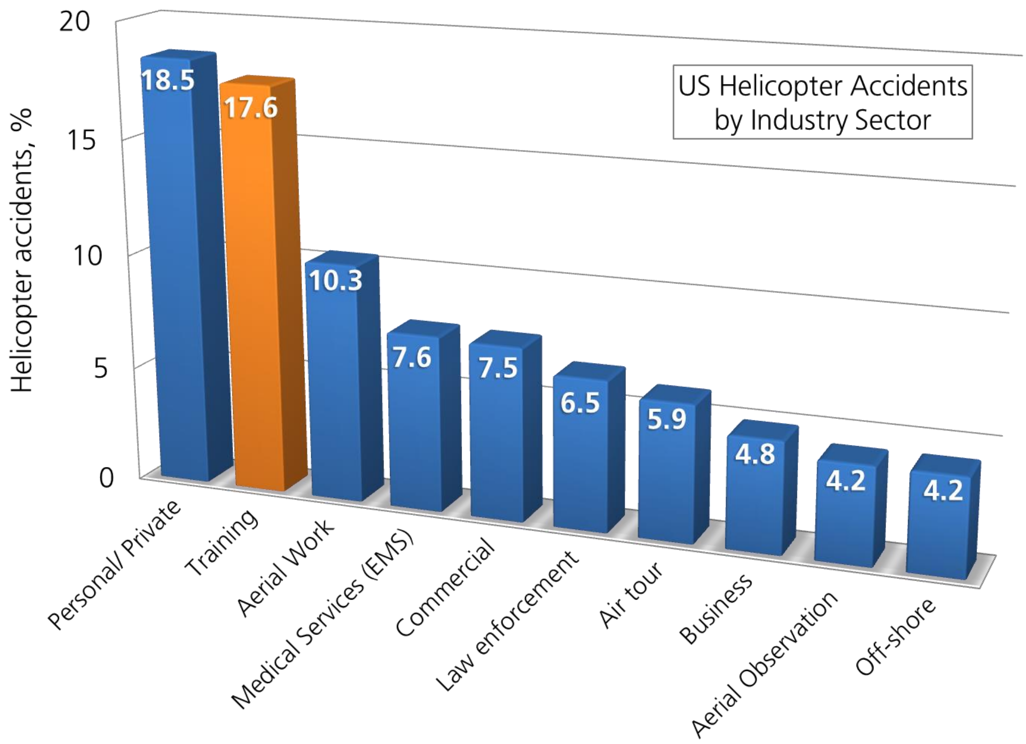

Figure 3.4: US helicopter accidents by industry sector, total 523 accidents, 10 main sectors, years 2000, 2001 and 2006 - adapted from [22]

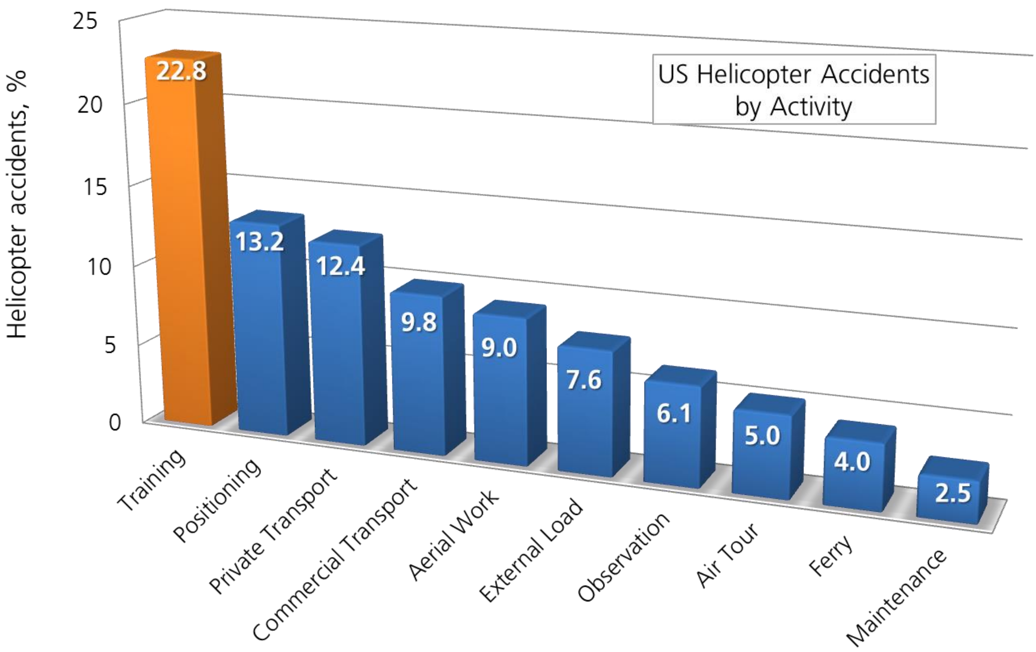

Figure 3.5: US helicopter accidents by activity, total 523 accidents, 10 main activities, years 2000, 2001 and 2006 - adapted from [22]

3.3.2 The Control Interference as Cause of Flight Accidents

The IHST's thorough investigation analyzed the immediate causes of accidents in flight training. The classification by occurrence, as depicted in Figure 3.6, points to loss of control (LOC) as the most commonly cited causal factor [87]. The three leading errors that triggered the occurrence of LOC in training flights are shown in Figure 3.7. The second most frequently mentioned error was control interference (INT). The category of LOC-INT includes accidents resulting in inceptor jam due to control interference by pilots, passengers, objects, and by factors related to maintenance.

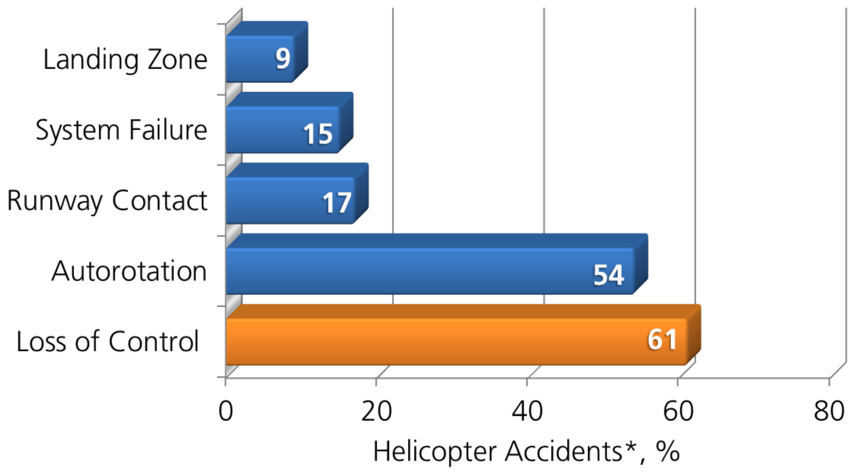

Figure 3.6: Main contributing factors of accidents related to instruction, years 2000, 2001 and 2006 - adapted from [87]

* Note: In the IHST, each accident could be placed in multiple occurrence categories, so the percentages shown are not intended to sum 100%

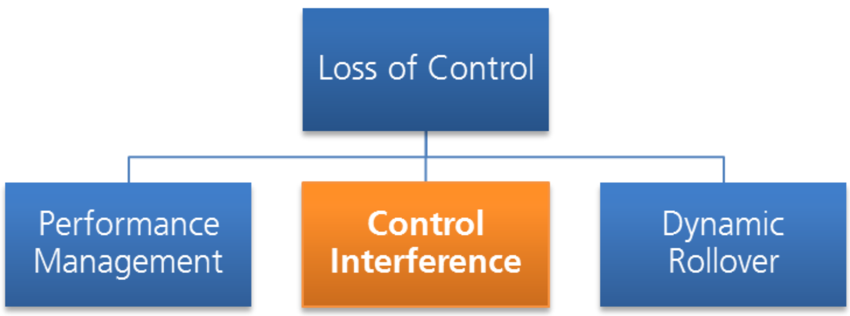

Figure 3.7: Most frequent errors of the loss of control occurrence in flight training, years 2000, 2001 and 2006 - adapted from [87]

Specifically, for flight training, these LOC events are mostly characterized by the interaction of the trainee and instructor pilots. Typical contributing factors for these events are: improper operation of the flight controls by the trainee pilot, failure of the trainee to relinquish control and inadequate supervision by the flight instructor.

Summaries of Accidents

In order to understand of the control interference error within the takeover control discussion, the summaries of four accidents were extracted from safety reports. The events represent the main characteristics of the LOC-INT accidents in training flights. The summaries were selected in the NTSB database, which contains accident reports with full narrative descriptions and probable causes of the occurrences.

Accident 1 - NTSB findings/probable cause: first pilot's failure to relinquish the flight controls (Bell 206B, 06/29/2001, 9am) [88]

"The helicopter rolled over onto its right side after the trainee pilot improperly positioned the cyclic control during liftoff to a hover. According to the instructor, the trainee was lifting the helicopter into a hover when he applied slight right cyclic. The instructor reported he was guarding the controls at the time and announced verbally he had the controls. As he attempted to lower the collective and center the cyclic, he noticed the trainee still had his hands on the controls and was continuing with a right cyclic input and increase in collective. The helicopter subsequently rolled onto its right side."

Accident 2 - NTSB findings/probable cause: first pilot's failure to relinquish the flight controls (EC120B, 02/03/2007, 2pm) [89]

"According to the FI, the pilot lifted the helicopter to a hover, and it began to rotate to the left. The FI instructed the pilot to 'add right pedal, add right pedal', but the helicopter continued to rotate to the left. The FI attempted to apply pressure on the right pedal, but the pilot 'panicked and froze' on the flight controls. The FI stated that he yelled to the pilot, 'I have the controls', but the pilot did not respond. The FI stated that he was unable to overcome the pilot's strength on the flight controls. The helicopter's tail rotor struck the ground, and the helicopter rolled over on its right side. Examination of the helicopter revealed the tail boom separated from the fuselage and main rotor blades were destroyed."

Accident 3 - NTSB findings/probable cause: trainee's inadvertent control interference, which the flight instructor was unable to overcome (R44 II, 06/14/2008, 11am) [90]

"The flight instructor was having the trainee practice landing approaches. With an airspeed of 60 to 65 knots, the trainee initiated a left base turn, lowering the collective, and adding aft cyclic for a normal approach to an open field. During the turn, the instructor noted that the helicopter was descending faster than anticipated, and that 'the collective was too far down, the cyclic was too far back, and [the trainee] had a tight hold on both controls'. The instructor attempted to regain control but could not move the collective or cyclic due to the trainee's grip on the controls. The instructor said that no words were spoken as he struggled with the trainee for control of the helicopter for a period of 3 to 4 seconds. The helicopter landed hard, rolled onto its left side, and instantly caught on fire. Both occupants exited the right door. The helicopter was destroyed by fire."

Accident 4 - NTSB findings/probable cause: first pilot's failure to relinquish the flight controls (Bell 206B, 03/15/1989, 5pm) [91]

"During an instructional flight, the flight instructor directed the trainee to make a normal takeoff. The instructor was following the trainee on the controls when the trainee suddenly moved the cyclic to the left. The helicopter started to roll to the left. The instructor could not overpower the trainee and regain control before the helicopter rolled over on its left side. There were no noted mechanical failures or malfunctions with the helicopter."

Analysis of Accidents during Takeover Control

There are common characteristics in the aforementioned accidents, as follows:

- No mechanical or flight control anomalies were reported.
- The accidents occurred in day, visual meteorological conditions.
- One of the probable causes of these accidents is the trainee's improper use of the flight controls.
- The instructor was guarding the controls before s/he attempt to takeover control.
- The instructor loses control of the helicopter, resulting in collision with the ground.

The sequence of actions is very similar in the accident descriptions. Initially, an improper control handling by the trainee preceded the takeover control attempt. Then, the lack of positive transfer of control caused difficulties in the controllability of the helicopter. The main roots of the problem were: the trainee froze on the controls; or failed to relinquish control to the instructor; or interfered inadvertently on control.

The mechanical linkages across the cockpit provides force feedback for the pilots, so a force fight condition is likely to last only a few seconds, which corresponds to the response time of the pilots. However, these accidents expose two limitations of the FCS. Firstly, the pilot who is taking over control (FI/PM) only has control authority if the other pilot (trainee/PF) recognizes the ongoing maneuver and reacts quickly by relinquishing inceptors. Secondly, even if the trainee pilot recognizes the control transfer maneuver, a brief force-fighting condition (3 to 4 seconds was reported in one occasion) may lead to the loss of control of the helicopter.

In the end, the loss of control was caused by the inaccurate control deflection and the proportional variation of the helicopter attitude, both outcomes triggered by the brief force fight. Given the conditions described in the accident summaries, it is hypothesized that the oscillations led pilots to experienced poor flight predictability and high workload, exceeding the FI's capacity to maintain the flight control.

3.4 Concluding Remarks

This chapter addressed the following topics:

- The cross-cockpit coupling produces fast reflexive motor responses that do not require high cognitive demands of the pilot to comprehend the haptic stimulus.
- The absence of inceptor cross-cabin coupling, or the inappropriateness in its implementation, may adversely affect the awareness of the pilots in the tasks of monitoring the helicopter states and monitoring the inputs of the pilot flying.
- The inceptor coupling can influence the situation awareness by helping to predict near future of the helicopter through the force feedback.
- Aviation agencies recommend the action of takeover control by the pilot monitoring or the instructor pilot if the flight safety is threatened.
- The flight training imposes additional risks to the instructor pilots in case of takeover control, due to the possibility of control blocked by the trainee pilots.
- Loss of control accidents, particularly in flight training, may be caused by the interaction of pilots with controls during takeover control. This problem is referred to as control interference, in which difficulties in the controllability of the helicopter were produced by the improper control handling of the trainee pilot.

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4 Variable Inceptor Coupling Design

This chapter describes the variable inceptor coupling design and its functional approach. The development of four inceptor coupling configurations to be tested in the experimental evaluations is described within the core system. The hallmark of the design consists not only on the core system (inceptor coupling/decoupling logic), but also on the supplementary structure, which includes the tactile cues, warning, trim, and feel systems.

4.1 Hypotheses and System Development

Two hypotheses were developed to address the main problems described in the preceding chapter, which are related to the situation awareness (SA) and takeover control. The first hypothesis is that the inceptor coupling can provide adequate situation awareness to monitor the performance of the pilot flying. The uncoupled inceptor design is in marked contrast to the permanently coupled inceptors and is valuable to highlight the quantitative awareness difference between these systems.

The second premise is that a decoupling system can be helpful for the takeover control maneuvers performed by the PM/FI. The decoupling possibility is henceforth mentioned as the variable inceptor coupling, whereas the system without decoupling means is also referred to as the virtual rigid coupling.

Therefore, the system was developed to provide a comprehensive understand of the hypotheses. Table 4.1 describes the proposed design alternatives to test empirically the premises mentioned. Two major design alternatives are the coupled/uncoupled condition for the SA issue (Table 4.1; items a, and b) and the decoupling/no decoupling possibility for the takeover control maneuver (Table 4.1; items c, and d).

The implementation of the decoupling system considers the design of human–machine cooperation, as addressed in the next section.

Table 4.1: System design alternatives

Problem*	Item	Design Alternatives	Description
Situation Awareness	a)	Coupled Inceptor	Virtual rigid coupling
	b)	Uncoupled Inceptor	Inceptors summed inputs
Takeover Control	c)	Inceptor Coupling without Decoupling	Permanently coupled inceptors
	d)	Inceptor Coupling with Decoupling	Decoupling (Manual/Automatic)

* Problems as defined in Chapter 3 (items 3.2 and 3.3).

4.2 Design for Human-Machine Cooperation

The helicopter control via active technology can become an example of human-machine cooperation (HMC). In this mutual assistance, there is a two-way information flow. In one hand, the pilots apply inputs to the inceptors, whereby the data are transmitted to the FCC. On the other hand, the active inceptor system can convey tactile information to the pilots through the sticks. Moreover, the flight control computer has the ability to interfere in pilot's input and optimize the response of helicopter (e.g., adding filters and rate limiters).

According to the HMC definition, two agents are cooperating if each agent strives towards goals and can interfere with the other to make the other's activities easier [92], [93]. Thus, the crew in dual pilot helicopters, like the trainee and the FI, are examples of human-human cooperation.

The HMC is required because the FI (or the PM) may not have enough control authority to perform the takeover control. As defined by Millot *et al.* [94], authority relates to the decisional independence of the agent, who should decide and act alone on the process without requiring other agents for validating this decision or action. It is not the case of takeover control maneuver, which requires the consent of the pilot flying. Usually, the control request occurs simply verbally (announcing "I have control"); but eventually a physical override is demanded. The successful takeover control is only completed in case of understanding and collaboration of both pilots. Therefore, a variable inceptor coupling may be necessary to increase the FI authority for the task of takeover control.

4.2.1 Theory of Human-Machine Cooperation

In the cooperative activity, both the human operator and the machine can be modeled according to their capabilities. The machine is represented as the decision support system (DSS), which provides assistance to make the human operator's tasks easier and helps to prevent erroneous actions [94, p. 217].

Figure 4.1 illustrates the position of the DSS as the machine agent in a horizontal structure for HMC. Here, each agent (human and DSS) has the authority for performing their own tasks. A task allocator introduced at an upper level has the authority for sharing these tasks between the agents. The tasks can be allocated by human (explicit mode), or artificially (implicit mode). In case of conflict, the DSS must manage the interferences between their goals using two classes of cooperative activities. The first activity class, *Managing Interference* (MI), requires the ability to detect and manage interference between goals. The second activity class, *Facilitating Goals* (FG), requires the ability to make the achievement of the other agents' goals easier [95], [96].

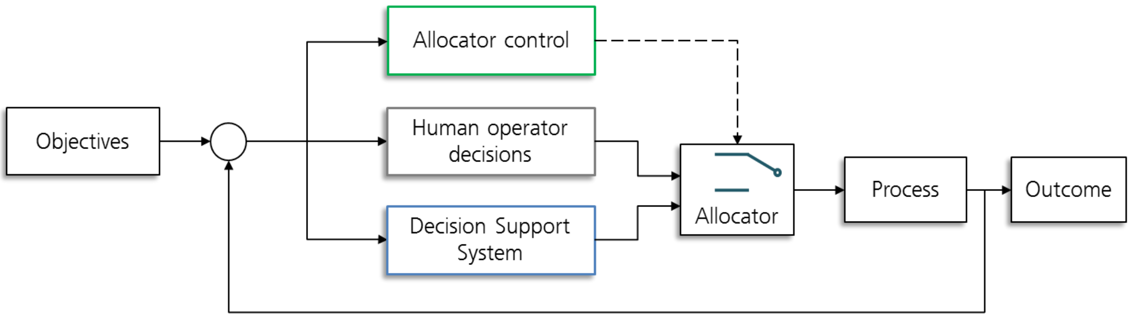


Figure 4.1: Structure of human-machine cooperation [97], [98]

4.2.2 Application of Human-Machine Cooperation

The variable inceptor coupling is a dedicated assistance tool and is designed to facilitate the pilot's duties regarding the tasks of monitoring the trainee pilot actions on control and takeover control, when applicable. Figure 4.2 shows the inceptor coupling system within the horizontal structure for HMC.

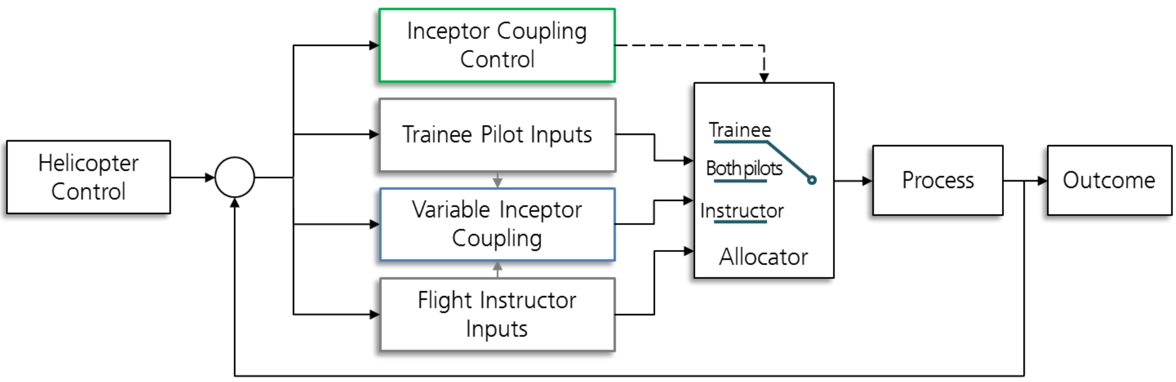


Figure 4.2: Variable inceptor coupling in horizontal structure for HMC

In this arrangement, the allocator is used to modify the coupling status (i.e., coupled or uncoupled inceptors across the cabin). The variable inceptor coupling provides the replication of the trainee's actions on control to the FI's inceptors. To achieve this goal, the *Inceptor Coupling Control* moves the allocator switch to the coupled inceptor position (dashed line), and all the trainee's inputs can be reproduced in the FI's control station. The awareness of the PM/FI is meaningful to the detection of abnormal conditions, the identification of the helicopter states and the definition of the corrective actions. As previously described, the status of the *Inceptor Coupling Control* can be modified by either the pilots using a pushbutton in the cyclic sidesticks (explicit mode), or by the variable inceptor coupling (implicit mode).

Ultimately, the authority of the PM/FI is relevant to perform takeover maneuvers as a recovery action. As human operators, the pilots shall be able to detect, prevent, or recover an unsafe behavior caused by another pilot or by automated decision-makers [94]. Therefore, the *variable inceptor coupling* (blue rectangle in Figure 4.2) is a DSS and shall be able to identify a conflict of pilots during the flight, which may arise as a dual input. The MI activity is performed by detecting the interference in the helicopter control through the force sensors, in addition to the deactivation of the trainee's inceptors, if certain conditions are reached.

The *variable inceptor coupling* not only changes the allocator from coupled to uncoupled status, but also modifies in the trainee's inputs, by actively adding tactile cues or varying the feel characteristics. It relates to the FG activity, which the ultimate goal is the improvement of the global performance of the pilot-inceptor cooperation during takeover control maneuvers. This approach is essential to implement the inceptor configurations to be tested, which are addressed in the next section.

4.3 Description of the Variable Inceptor Coupling System

The system block diagram was built upon the pilot-inceptor-aircraft loop previously showed in the Chapter 2, which is conveniently replicate in Figure 4.3. The AIS block is highlighted in green in the new picture. The *variable inceptor coupling* is a type of AIS and was developed to consider the electronic inceptor coupling in a dual pilot cabin. The system is depicted in Figure 4.4, and its subsystems are also emphasized in green colors.

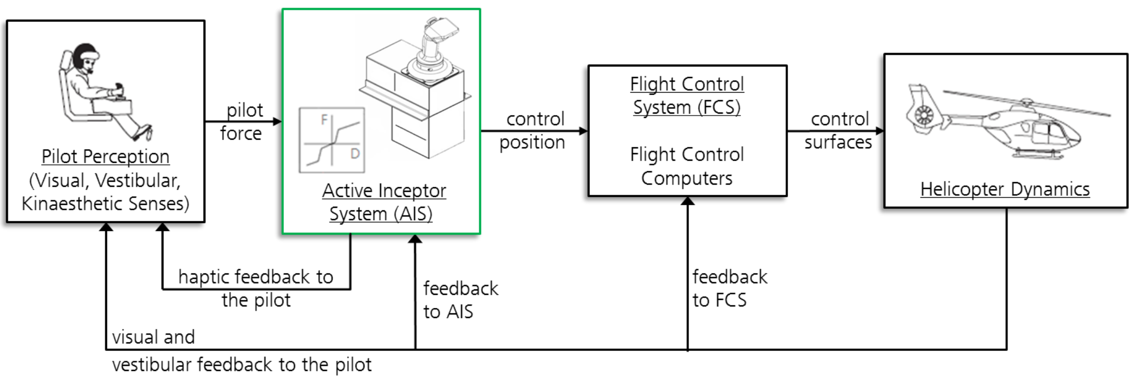


Figure 4.3: Pilot-inceptor-aircraft loop including AIS (highlighted in green) - adapted from [32]

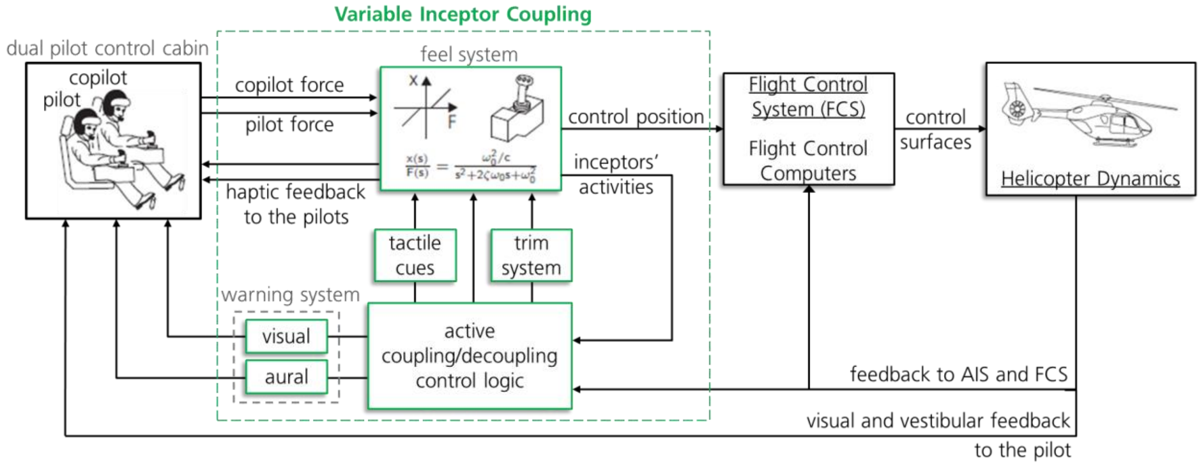


Figure 4.4: Pilot-inceptor-aircraft loop including variable inceptor coupling (highlighted in green)

The variable inceptor coupling is modelled in MathWorks' Matlab/Simulink [99] software environment using operational blocks to generate user defined control laws. The core subsystem consists of programming the logics to command the coupling and decoupling of the inceptors. Supplementary subsystems are the components associated to the tactile cues, warning system, feel characteristics, and trim setup. The overall functionality of the variable inceptor coupling system is explained through the description of each subsystem.

4.3.1 Active Coupling/ Decoupling Control Logic

The main subsystem aims to program functions to couple, decouple or recouple the inceptors. Applying the theory of the HMC to test the applicability of the system to address the problem related to control interference (Table 4.1), four inceptor coupling configurations were developed based on specific control laws. These are:

- *Configuration 0 (UNCP)*: Inceptors are permanently uncoupled, without force feedback relative to the other pilot's input.
- *Configuration 1 (BENCH):* Inceptors are permanently coupled; and no decoupling is available. The mechanical linkage of coupled inceptors is emulated; and the deflection of the inceptors related to the neutral position is the same in both control stations (pilot and copilot).
- *Configuration 2 (AUTO):* Inceptors are coupled; and the automatic priority logic can decouple inceptors if certain conditions are reached. In case of a 'force-fight' between the pilots (i.e., they apply inputs in different directions), a given force threshold is specified whereby the inceptor coupling is disengaged if the opposing forces surpass this threshold.

- *Configuration 3 (PUSH):* Inceptors are coupled; and the manual decoupling can be activated through the use of a priority pushbutton on the cyclic lever.

The features of each configuration are further explained, all based on preliminary tests of takeover control maneuvers performed by the FI.

Configuration 0 (UNCP)

In configuration 0 (UNCP), the inceptors of pilots are not coupled to each other. If just one pilot applies inputs, the helicopter attitude response corresponds to the actual inceptor position of the pilot flying. However, in case of inputs from both control stations, the algebraic summing of the sidesticks positions is averaged as output control signal. For example, if one stick is moved fully backwards and the other fully forwards, the resulting command is zero.

In case of simultaneous inputs of both pilots in the same direction, the resulting signal is saturated when a value corresponding to the sidestick maximum deflection is reached. So, if both sidesticks are moved more than half way backwards, the resulting command is equivalent to a single sidestick moved fully backwards.

Figure 4.5 exemplifies a representative case of takeover control using this configuration. The forces applied on active sidestick have direct influence on the vehicle response. The force plot indicates that initially the trainee (PF) flies the vehicle and there is no force input from the FI (PM). In the time t_i, the trainee's inappropriate input in a given axis is corrected by the interference of the FI. In this instance, the FI starts to move the inceptor in the opposite direction of the PF's stick. The takeover control is completed in time t_0, when the trainee relinquishes the inceptors. The difference between t_0 and t_i is the dual input time in configuration 0 ($t_{\mathrm{d}0}$), as follows:

$$t_{d0} = t_0 - t_i \tag{4.1}$$

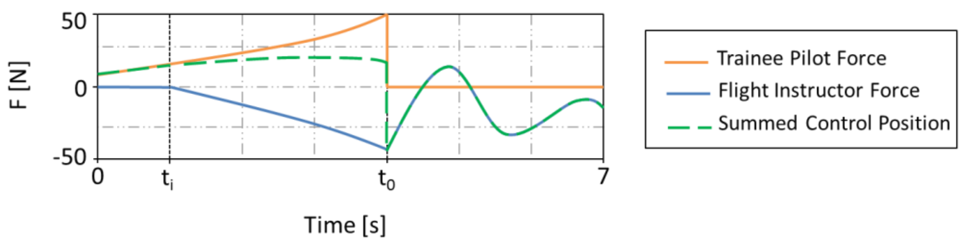


Figure 4.5: Configuration 0 of the variable inceptor coupling

The trainee recognizes the interference and relinquishes control at time t_0. Consequently, the inceptor returns to the neutral position and the corresponding force decreases to zero. The helicopter starts to respond to the sum of forces by triggering a sharp attitude change in direction of the FI's inputs.

After t_0, the FI has to adjust the inceptor position, which was excessively deflected to counter the inputs of the trainee pilot. The resulting control deflection rate is rather high, which can affect the FI predictability about the desired inceptor position. The attenuation of the oscillatory control deflection depends on the ability of the pilot to compensate the attitude variation.

Two major implications arise at this condition. Firstly, the actual position of the trainee's inceptors is not conveyed to the FI's stick to adjust the opposing force (before t_{i} and during t_{d0}). The natural reaction of pilots is increase the magnitude of the inputs, trying to shape up an effective response of the helicopter. Secondly, it is likely that the trainee takes some seconds (t_{d0}) to understand the interference of the FI due to the lack of force feedback. It should be noted that the delay of the trainee response time may be unbearable in time-critical conditions. In [10], it was verified a delay of 10 seconds in airplanes tasks to takeover during landing approaches using uncoupled inceptors, whereas the delay of the active coupled sticks was commonly up to 2 seconds.

Configuration 1 (BENCH)

In configuration 1 (BENCH), the sidesticks are programmed to act in unison as if mechanically linked, and no decoupling is available. The forces applied to one sidestick are transmitted to the other via electronic signal. This configuration, namely coupled or 'virtual rigid' mode, is considered the benchmark case, because practically all helicopters feature FCS without an inceptor decoupling across the cabin.

Figure 4.6 illustrates the configuration 1. The FI starts to counteract the pilot flying at time t_i, and the trainee realizes the interference and relinquishes control at time t_1. The sudden decrease of the opposing force causes a stepwise change in the summed forces at t_1. The forces generate a corresponding control deflection overshoot, based on the force control mechanical characteristics (e.g., force-deflection curve) and control laws. Ultimately, the vehicle attitude variations occur as a consequence of the control overshoots. The difference between t_1 and t_i is the force fight time in configuration 1 (t_{f1}), as follows:

$$t_{f1} = t_1 - t_i \tag{4.2}$$

Since the inceptor coupling provides force feedback regarding the actions on control, t_{f1} is likely to last only a few seconds. In order to simulate a realistic scenario, t_{f1} is defined based on two references. In the first one, as mentioned in the configuration 0, the normal pilot response time to interferences on coupled active inceptors is pointed out as up to 2 sec [10]. Moreover, the UK Defence Standard [100] defines the pilot response time for attentive hands-on operation as 1.5 seconds, which corresponds to the sum of decision time (1.0 second) and reaction time (0.5 seconds). The definition of attentive hands-on is suitable to the flights near the ground and obstacles, just as the tasks of monitoring the pilot flying and takeover control. Thus, for the present thesis, the realistic t_{f1} was defined as 1.5 seconds, with ±0.5 seconds of tolerance.

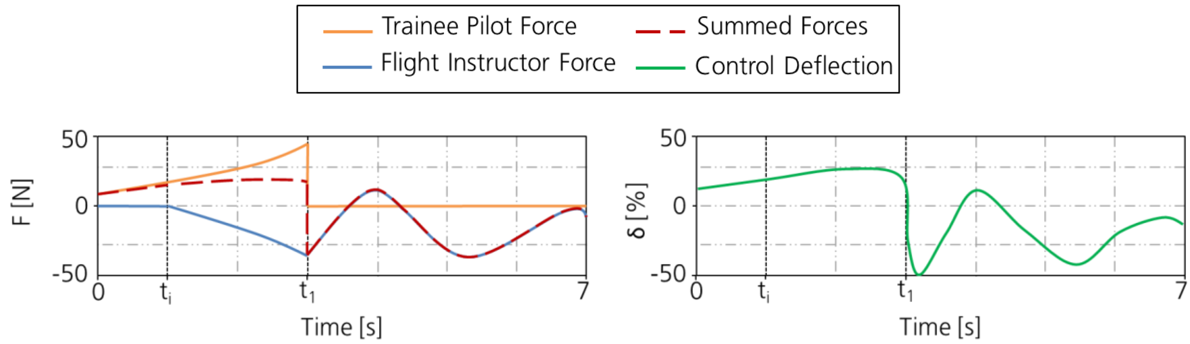


Figure 4.6: Configuration 1 of the variable inceptor coupling

Two limitations can be associated with the inceptor coupling system featuring the configuration 1. Primarily, the success of the takeover maneuver depends on the understanding of the trainee to relinquish control. It should be noted that the pilot response time can be adversely affected in demanding situations. If a long period of the so-called force-fight occurs, the controllability of the vehicle may be compromised. The second limitation is that even when t_{f1} lasts only a few seconds (e.g., 2 sec), this brief moment when the pilots are flying together may be enough to cause a significant impact on the control deflection, including oscillations that can last for some seconds after the handover, as exemplified in Figure 4.6.

Configuration 2 (AUTO)

In configuration 2 (AUTO), the automatic decoupling function is activated through the forces applied by pilots according to the information provided by the force sensors. An important design consideration is the definition of which control station will retain full control authority (single pilot priority) and which one will have no control authority (deactivated pilot). In this thesis, the functions are programmed to prioritize the control cabin of the pilot who is taking over control (FI). If the system detects the unsafe condition (two pilots flying at the same time) and the force threshold is reached, the trainee pilot input is deactivated. Thus, the FI's authority is increased by removing the influence of the trainee pilot on the task of takeover control.

Figure 4.7 illustrates the automatic inceptor decoupling. The time t_2 corresponds to the moment of the decoupling, and t_{f2} is the force fight time in configuration 2, as shown below.

$$t_{f2} = t_2 - t_i \tag{4.3}$$

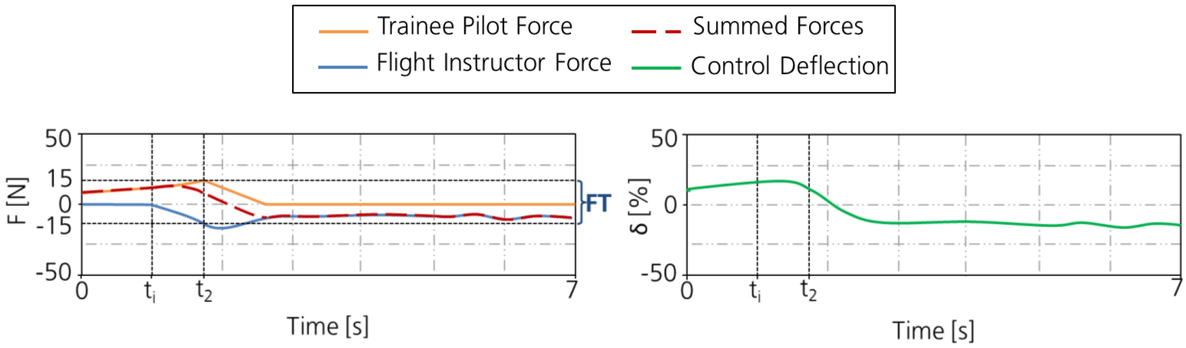


Figure 4.7: Configuration 2 of the variable inceptor coupling - FT: force threshold

A function is implemented to alleviate the control overshoot. A force fading is employed in the configuration 2 to compensate the opposing force after the system commands the decoupling. Namely Counter Force, the force fading logic is implemented to alleviate the residual oscillations in control deflection. This function is described in the next subsection (4.3.2).

Table 4.2 correlates the automatic logics to the cooperative activities of the variable inceptor coupling acting as a DSS, according to the HMC theory.

Table 4.2: Cooperative activities of the variable inceptor coupling

Variable Inceptor Coupling Logic	Cooperative Activity	Description
Automatic Inceptor Decoupling	Managing Interference	Increases FI authority if force threshold is reached by deactivating the trainee pilot
Counter Force	Facilitating Goals	Trainee force fading logic makes the takeover control task easier to the FI

Configuration 3 (PUSH)

Configuration 3 (PUSH) corresponds to the deactivation of the inceptor coupling via the pushbutton on the cyclic. The pilot who presses the button has full authority, and, from that moment on, is the only pilot flying the vehicle. Similarly to configuration 2, the force fight time in configuration 1 (t_{f1}) can be reduced if pilots decouple inceptors timely. In this configuration, however, the decision to decouple inceptors is manual, requiring pilot judgment to evaluate the best moment to takeover control. In this respect, configuration 3 offers more flexibility than configuration 2 at the cost of mental demands. The time t_3 corresponds to the moment of the manual decoupling (pushbutton), and t_{f3} is the force fight time in configuration 3, as shown in Figure 4.8.

$$t_{f3} = t_3 - t_i \tag{4.4}$$

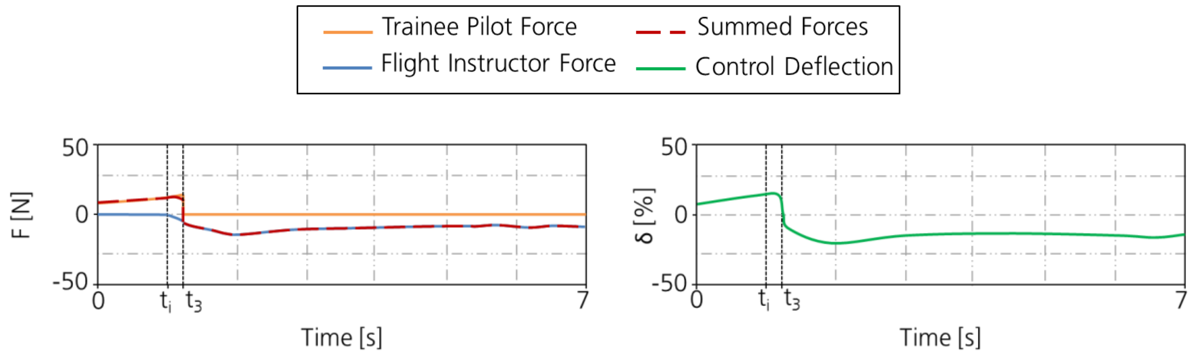


Figure 4.8: Configuration 3 of the variable inceptor coupling

Once the inceptors are decoupled, the same pushbutton can be used to reverse the delinking and recouple the cross-cabin controls inceptors. A fading time is applied to avoid adverse helicopter attitude transients during the inceptors' recoupling. In other words, once the recoupling is commanded, the functionalities in both set of inceptors is only activated when the inceptors share the same position (coupled inceptors).

4.3.2 Tactile Cues

Active inceptors are capable of mechanizing a wide variety of tactile cues for the pilots. Two haptic features are triggered in case of automatic decoupling: a force fading function (i.e., Counter Force) and a stick shaker in cyclic lever (namely, Cyclic Shaker).

Counter Force as a Force Fading Function

The Counter Force is an adaptive ramp to reduce the sudden transients in control deflection caused by the deactivation of one control station in the automatic decoupling. As indicated in Figure 4.9a, the residual oscillations in control deflection can be detected in case of abrupt deactivation of one pilot, due to the application of force at the moment of the decoupling (t_2). The active force variation aims to compensate the stepwise control caused by the automatic decoupling and attenuate the adverse helicopter attitude oscillations.

This force fading function retains the force applied by the opposing pilot (in this case, the trainee pilot) at the moment of the decoupling (t_2). The force is reduced gradually to zero in one second, providing the opportunity to the FI pilot to steadily alleviate the force during this period of time. The time frame of one second was suggested in a previous study [101]. This work analyzed the impact of the control power reduction (relation control deflection versus helicopter attitude variation) in takeover control maneuvers. Pilots increased the control deflection if the reduction occurs during two or more seconds. But one-second power lessening achieved the same performance as the tasks with full control power, indicating that pilots can compensate the variation during this period without compromising the performance.

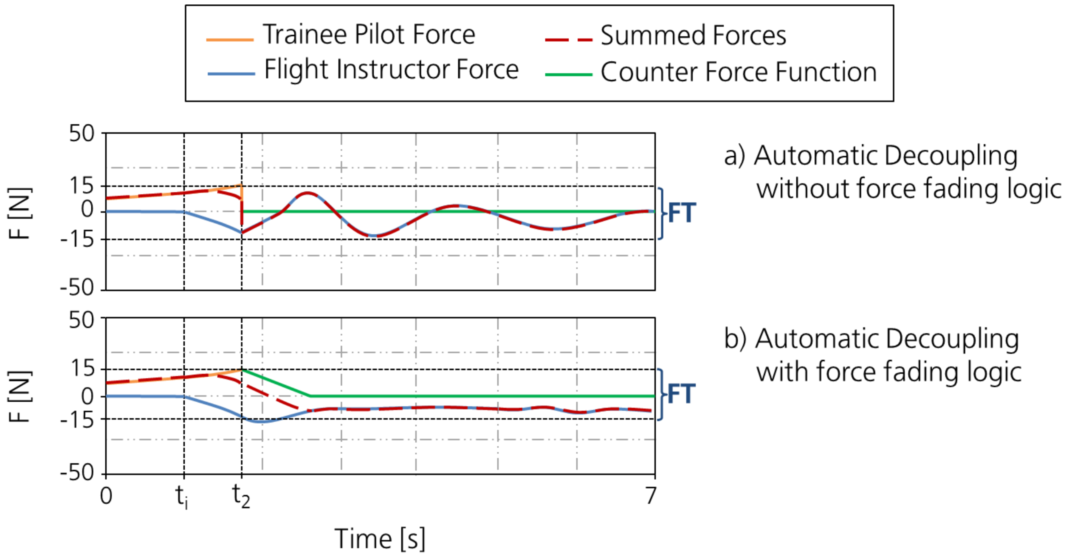


Figure 4.9: Automatic inceptor decoupling, force fading function off (a) and on (b)- FT: force threshold

Cyclic Shaker as Tactile Alert

The Cyclic Shaker is a pilot assistance function to identify the automatic inceptor decoupling without the need for visual confirmation. The shaker activates a sinusoidal waveform in roll axis, which is superimposed over the nominal feel of the inceptor. The Cyclic Shaker aims to alert the pilots without excessive inceptor travel that could impact adversely the pilot controllability. To this end, the function includes high frequency (60 Hz), low amplitude (5% control deflection), and width of 8 pulses.

4.3.3 Warning System

According to aviation standards, a warning system is necessary for conditions that require immediate flight crew awareness and response [102]. Considering the deactivation of one control station as a critical condition that may lead to severe consequences for flight safety, a warning system is judged necessary to provide pilot's awareness regarding the inceptor coupling status.

It should be noted that a single alert, as the Cyclic Shaker function, is not sufficient. According to the FAA guidance, warning alerts must provide timely attention-getting cues through at least two different senses by a combination of aural, visual, or tactile indications [102]. Thus, a dedicated warning system including visual and aural aids is developed based on an extensive list of design considerations and FAA regulatory guidance material contained in [103]. Table 4.3 presents a summary of the main guidelines applied on the development of the warning system.

Table 4.3: Guidelines for development of the warning system

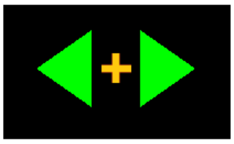
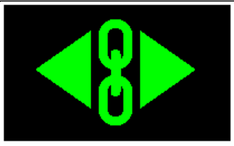
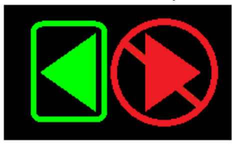
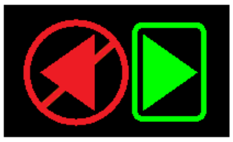
Topic	Design Considerations	Recommendation based on FAA Regulatory and Guidance Material	Reference
Location	Alerts shall be clearly visible and attract an appropriate amount of attention [103]	Time-Critical warning visual information should appear in each pilot's primary field of view[1].	[105] App 1, §3.a
Color	Visual alert indications using color shall be appropriate and easily discriminated [103]	If warning lights are installed in the cockpit, they must be: a) Red, for warning lights (hazard which may require immediate corrective action); b) Amber, for caution lights (possible need for future corrective action); c) Green, for safe operation lights.	[102] §e, 1, i
Symbology	All symbols shall be distinctive and clearly depicted [103]	The symbology shall be readily discernible and should be legible and readable within the specified viewing envelope.	[106], [107] 4.2.1
Voice alerts	Voice alerts shall be distinctive and intelligible [105]	The alerting elements for time-critical warnings should include unique voice information or unique tone, or both, for each alerting condition.	[105] §6.b, and App. 2 §3.f, 1, a

The warning system implemented in the variable inceptor coupling is shown in Table 4.4 for each of the four testing configurations. The primary flight display (PFD) is used as a practical and preferred display for displaying the time-critical warning alerts since the pilot constantly scans the PFD. The symbology consists in shapes to convey information regarding system status and is always presented to pilots in the PFD (Figure 4.10). The chain symbol indicates the coupled inceptor condition.

[1] Primary field-of-view is based on the optimum vertical and horizontal visual fields from the design eye reference point that can be viewed only with eye rotation [104]. This field of view is defined as ±15° relative to the normal line-of-sight, which is established at 15° below the horizontal plane of the pilot's eyes looking forward. This area is normally reserved for primary flight information and high priority alerts.

The aural stimulus to attract attention of the pilots is triggered when there is a transition among the status of the four inceptor coupling (coupled, uncoupled, left pilot priority, and right pilot priority). The voice messages are computed generated and uses dissimilar keywords for each status.

Table 4.4: Warning system in the variable inceptor coupling

Design Topic	Configuration		
	Config. 0 (UNCP)	Config. 1 (BENCH)	Config. 2 (AUTO) and Config. 3 (PUSH)
Location	Warning visual information is displayed in each pilot's PFD		
Color and Symbology	 Uncoupled Inceptors (inputs are summed)	 Coupled Inceptors (emulation of mechanical linkages)	 Coupled Inceptors;   Left pilot priority; or right pilot priority
Voice alerts	"Flight controls uncoupled"	"Flight controls linked"	"Flight controls linked"; "Priority: left pilot"; or "Priority: right pilot"

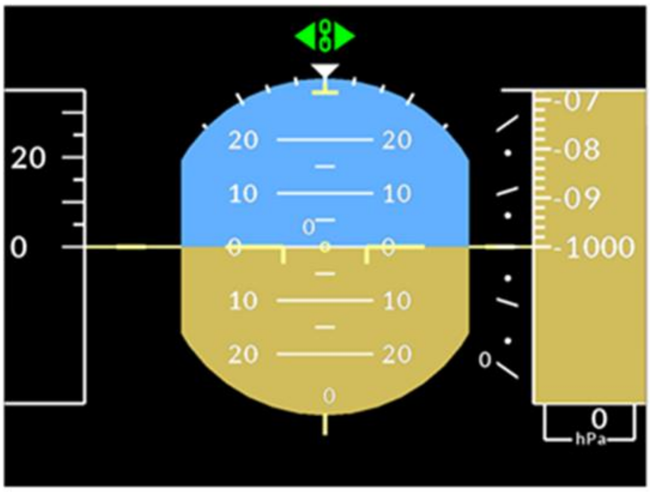


Figure 4.10: Position of the warning system symbology in the PFD

4.3.4 Feel System

Description of the Force Control Mechanical Characteristics

The force control mechanical characteristics (FCMC) of active sidesticks can be tuned via data interface in real-time by the computers of the system. Main emphasis of this work is laid on the cyclic sidestick, but the FCMC settings require the definition of the static and dynamic parameters of all inceptors (cyclic, collective and pedals). Some of the main concepts for the definition of the FCMC are described in this subsection.

One of the key parameters of the static control characteristics is the force-deflection curve in force-free neutral position (unique trim controller). As depicted in Figure 4.11, the definition of two nonlinearities is important to reproduce a realistic characteristic curve: the breakout force (F_b), and the hard stop (maximum deflection, $x_{\max}$). A breakout force is needed to prevent inadvertent inputs at the center position, and to overcome the impact of any friction when inceptors are centering [108]. The deflection, also named as control travel, is important to avoid overly sensitive control (low travel) or uncomfortable wrist movement (high travel) [108].

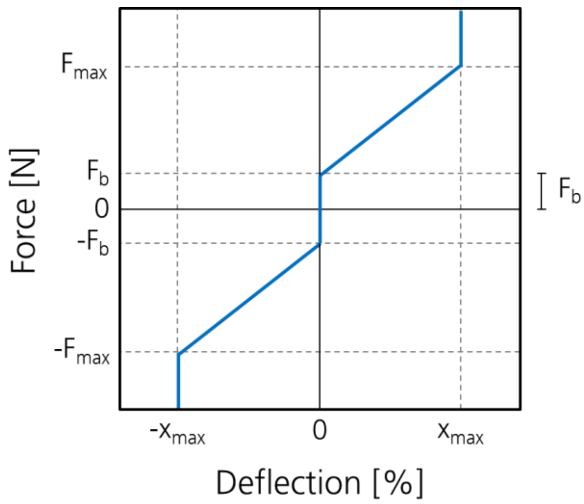


Figure 4.11: Typical control deflection curve including breakout force and hard stop

The force deflection gradient k is defined as:

$$k = \frac{F}{x} \tag{4.5}$$

The force deflection gradient may be nonlinear, so k is only defined locally. In the case of Figure 4.11, the gradient can be calculated as:

$$k = \frac{F_{max} - F_b}{x_{max}} \tag{4.6}$$

The lateral sidestick characteristics can be set asymmetrically about trimmed position, which is essential to account for different capabilities of the human arm and wrist [38]. Commonly, the outboard forces are lighter than the inboard forces in roll axis.

A mechanical system is developed and showed in Figure 4.12 to describe the dynamic properties of the control force system. The translational behavior of the active inceptors can be modeled as a mass-spring-damper system [109]. The force F is proportional to the displacement x of the sidestick with the mass m. The forces are counteracted by the spring force $k = k(x)$ and the damping coefficient b.

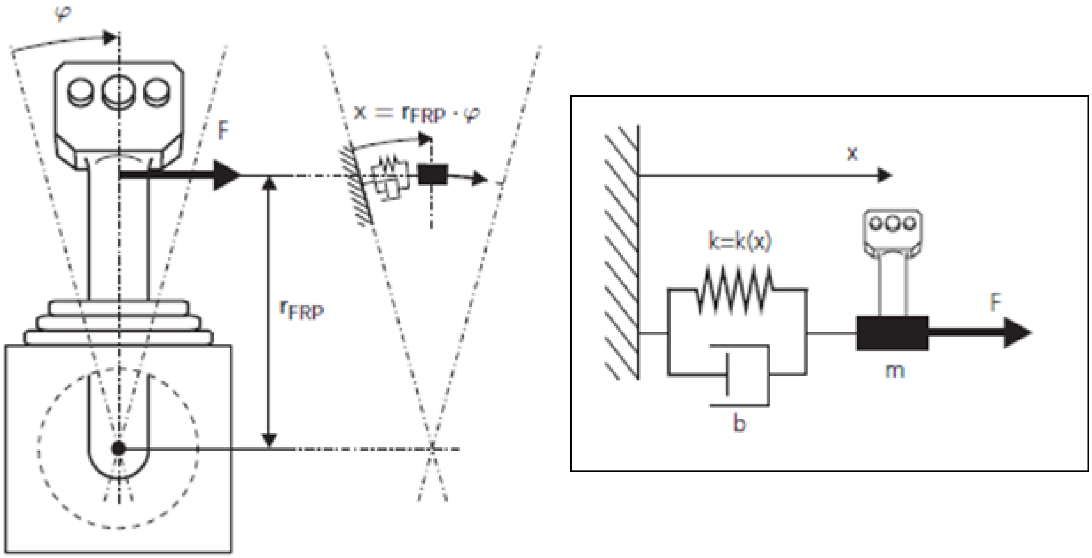


Figure 4.12: Control system of an active sidestick [109]

Similarly, the displacement of the active sidesticks is the result of the forces entered by the pilot on the inceptor. The point that represents the application of the pilot forces is the finger reference point (FRP), which is typically defined as the middle finger position. The force input is perpendicular to the line connecting the FRP and the pivot point. Therefore, as presented in Figure 4.12, the deflection of the inceptor is the angular control displacement φ times the pivot arm r_{FRP}, which is the distance between the FRP and the pivot point in the plane of rotation.

Well damped inceptors are found desirable to prevent over-controlling, which can result in a jerky ride quality [38]. The damping ratio D is given by the expression

$$D = \frac{b}{2\sqrt{k\,m}} \tag{4.7}$$

The natural frequency ω_n is written as

$$\omega_n = \sqrt{\frac{k}{m}} \tag{4.8}$$

The dynamic control characteristics can be represented as a second order system based on the natural frequency ω_n and the damping ratio D [39] according to the transfer function:

$$\frac{\delta_x}{F} = \frac{\omega_n^2/k}{s^2 + 2Dw_ns + w_n^2} \tag{4.9}$$

where δ_x is the control deflection. Thus, the variations of the natural frequency are equivalent to variations of the stick inertia m [39].

Active Sidestick Calibration

For the evaluation of the variable inceptor coupling, two pairs of active sidesticks and two active pedal units were newly acquired (Figure 4.13). The inceptors are manufactured by Wittenstein Aerospace & Simulation GmbH, and their specifications are outlined in Table 4.5.

Table 4.5: Inceptor specification [110], [111]

Inceptor Specification	Sidestick		Pedals
	Longitudinal	Lateral	
Reference Point for Force Application [mm]	205	205	185
Maximum Deflection [deg]	±18.5	±18.0	±18.0
Maximum Deflection [mm]	±66.2	±64.4	±58.1
Maximum Nominal Force [N]	±142	±142	±535

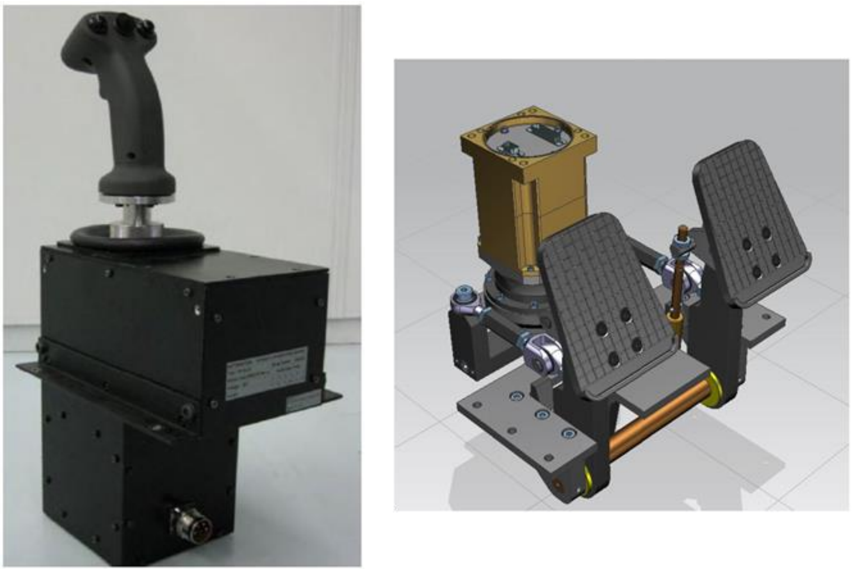


Figure 4.13: Active sidestick and active pedal unit

The calibration of the inceptors is the first step for the definition of the feel characteristics. The analysis of the internal forces and position sensors ascertains the ability of the AIS to accurately modify the parameters via control software. The procedures and results are documented in two specific reports, one for the sidesticks [110] and another for the pedal units [111]. The angles were measured by an amplifier in combination with an inclinometer; and the forces were adjusted via a tensile and compressive force gauge. After the modification of the calibration factors, the system was judged satisfactory to reproduce a given control force characteristic without systematic error.

The analysis of the dynamic performance was verified by model identification. For this purpose, values of ω_n (between 1 and 10 Hz) and *D* (between 0.7 and 4) were tested. Figure 4.14 exemplifies the investigation, where the second order reference model (red), the measured values (blue) and the identified model (black dashed) can be read off in the Bode diagrams. In addition, the bandwidth limit is indicated by a black vertical line within the coherence plot, corresponding to the frequencies with coherence below 0.9.

The dynamic performance is given only if the magnitude of the measurement does not deviate more than 6 dB and the phase does not deviate more than 45 degrees from the reference model [7]. These limitations also determine the bandwidth of each configuration. In the investigation, the bandwidth limits in terms of magnitude and phase were always reached after the value of 0.9 for the coherence. The reference model represents the target values and the identified model indicates the actual values. In general, the identified values are on the same path as the measured values up to the limit marked in the Bode diagram, showing that the measurements are well reproduced by the identified model.

Feel Characteristics for the Variable Inceptor Coupling

Since the set of inceptors is tested for the first time for the present thesis, the AIS nominal setting of a previous study was employed as the initial reference force-feel configuration [33]. In this work, the FCMC were optimized by Empire Test Pilot School (ETPS) trainees during an ACT/FHS flight campaign in Braunschweig in 2013 [112]. The reference study tested the cyclic and collective active sidesticks for an attitude command response type[2]. However, the sidesticks in [33] and the available Wittenstein inceptors are manufactured by different companies (*Stirling Dynamics* for the cyclic control and *Liebherr Aerospace* for collective control). There are significant dissimilarities related to

[2] In an attitude command response type, the stick deflections from neutral position are proportional to the aircraft attitude. It differs from rate command, whereby pilot stick deflections away from the stick neutral location are proportional to the aircraft angular rate response [108].

dynamic and static limits, which consequently affects the performance. So, the adjustment of the reference values was mandatory.

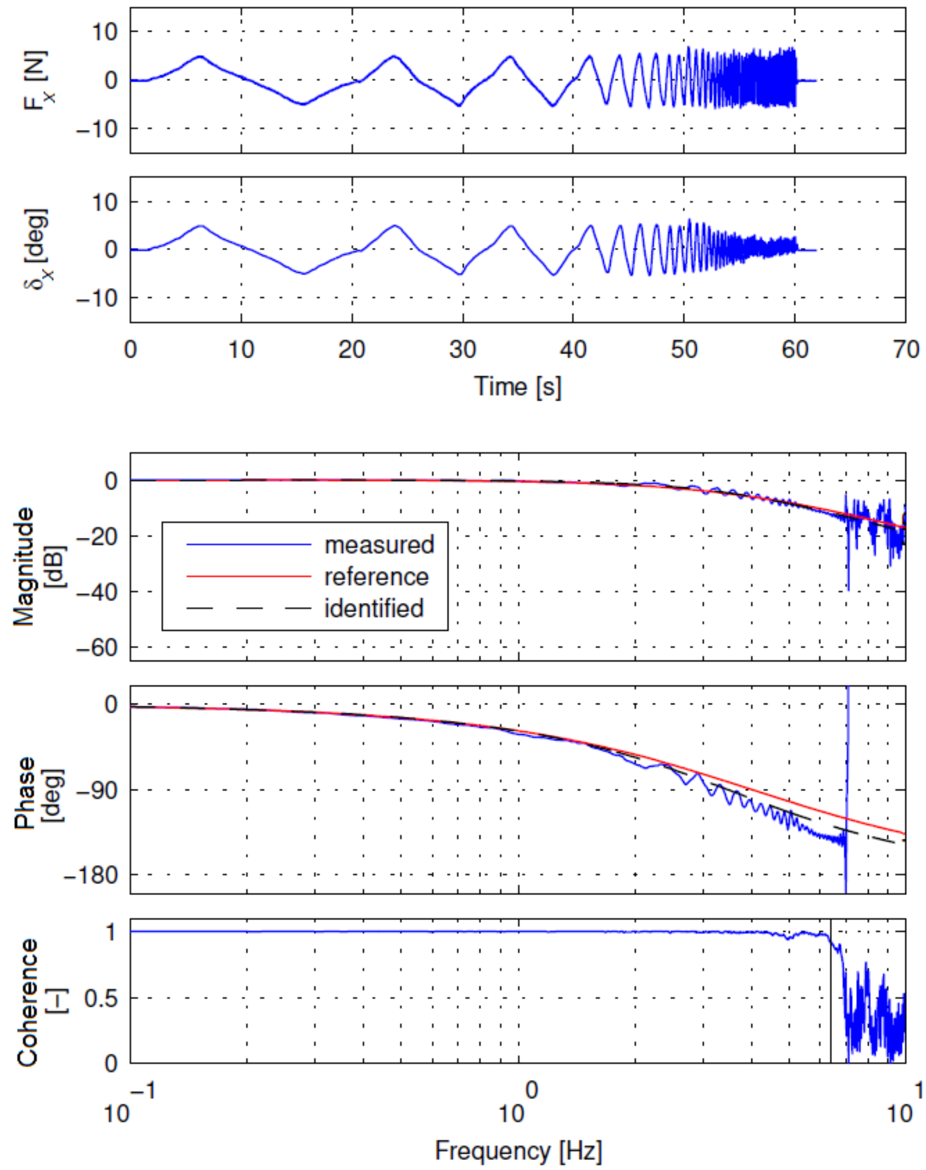


Figure 4.14: Bode diagram of active sidestick at ω_n= 4 Hz and D = 1 (pitch axis) [110]

The investigation of the appropriate FCMC was performed through the feedback of one test pilot in simulator practices, following the approaches mentioned in [38], [113] and described hereafter. The parameters (e.g., damping, natural frequency, force deflection gradient, breakout force, and maximum deflection) were iteratively changed until the test pilot approved the modification based on his subjective opinion. Two mission task elements (MTE) from the Aeronautical Design Standard (ADS) 33E [114] were chosen as evaluation maneuvers for this test: the Hover MTE for low-speed maneuvering using small precise inputs, and the Slalom MTE for intermediate speed maneuvering using large inputs. Beginning with the reference configuration, parameters varied in random order. In the end of the evaluations, the ratings and parameters were revealed to the pilot, who could fly again to confirm the ratings. In case of divergence between the optimum setting for the hover and the slalom tasks, intermediate values were suggested for new examinations. The optimization of the control characteristics ended when the intermediate value did not compromise the best performance for each task.

The final FCMC setting is defined in Table 4.6 for each of the four axes: pitch, roll, heave, and yaw. The roll parameters are complemented in Table 4.7.

Table 4.6: Force control mechanical characteristics

Characteristics	Value			
	Pitch	Roll	Heave	Yaw
Control travel [deg]	±17	±17	±17	±17
Control travel [mm]	±49.1	±49.1	±59.6	±51.7
Deflection range [%]	±50	±50	±50	±50
FRP [mm]	165.5	165.5	201.0	185.0
Force gradient [N/%]	0.4	(Table 4.7)	0.4	0.6
Master curve [N/%]	1.1	0.5	0.5	2.0
Breakout force [N]	1.5	1.0	0.0	0.0
Maximum force [N]	±20.2	+11.0; -13.4	±17.5	±32.0
Natural frequency [Hz]	4.0	4.0	2.8	3.2
Damping ratio [-]	1.2	1.2	1.0	1.2
Control rate [deg/sec]	30	30	50	60
Friction [N]	0	0	2.0	2.0
Stick Inertia [kg]	0.65	(Table 4.7)	0.92	0.77

Table 4.7: Force control mechanical characteristics: additional roll values

Characteristics	Value			
	Position 1	Position 2	Position 3	Position 4
Position range [%]	-50 to -15	-15 to 0	0 to 15	15 to 50
Softstop amplitude [N]	3.2	3.0	2.3	1.0
Force Gradient [N/%]	-0.19	-0.38	0.30	0.15
Stick Inertia [kg]	0.31	0.61	0.49	0.25

The FRP of the collective and cyclic are different, because the generic sticks (Figure 4.13) were replaced by representative grips of the EC-135 helicopter, as presented in Figure 4.15. Therefore, the point of force application differs between the left and right hand sidesticks.

Figure 4.15: Collective grip (bottom left), cyclic grip (bottom right), and 45° collective arrangement (top)

The cyclic lever includes linear force-deflection gradient in pitch and non-linear gradient in roll, due to the anthropometry of the human arm (greater force in the roll inboard direction than the roll outboard direction). The curves of the four axes are shown in Figure 4.16. The force deflection curves for the same axis remained identical on both pilot and copilot control stations to minimize transient occurrences.

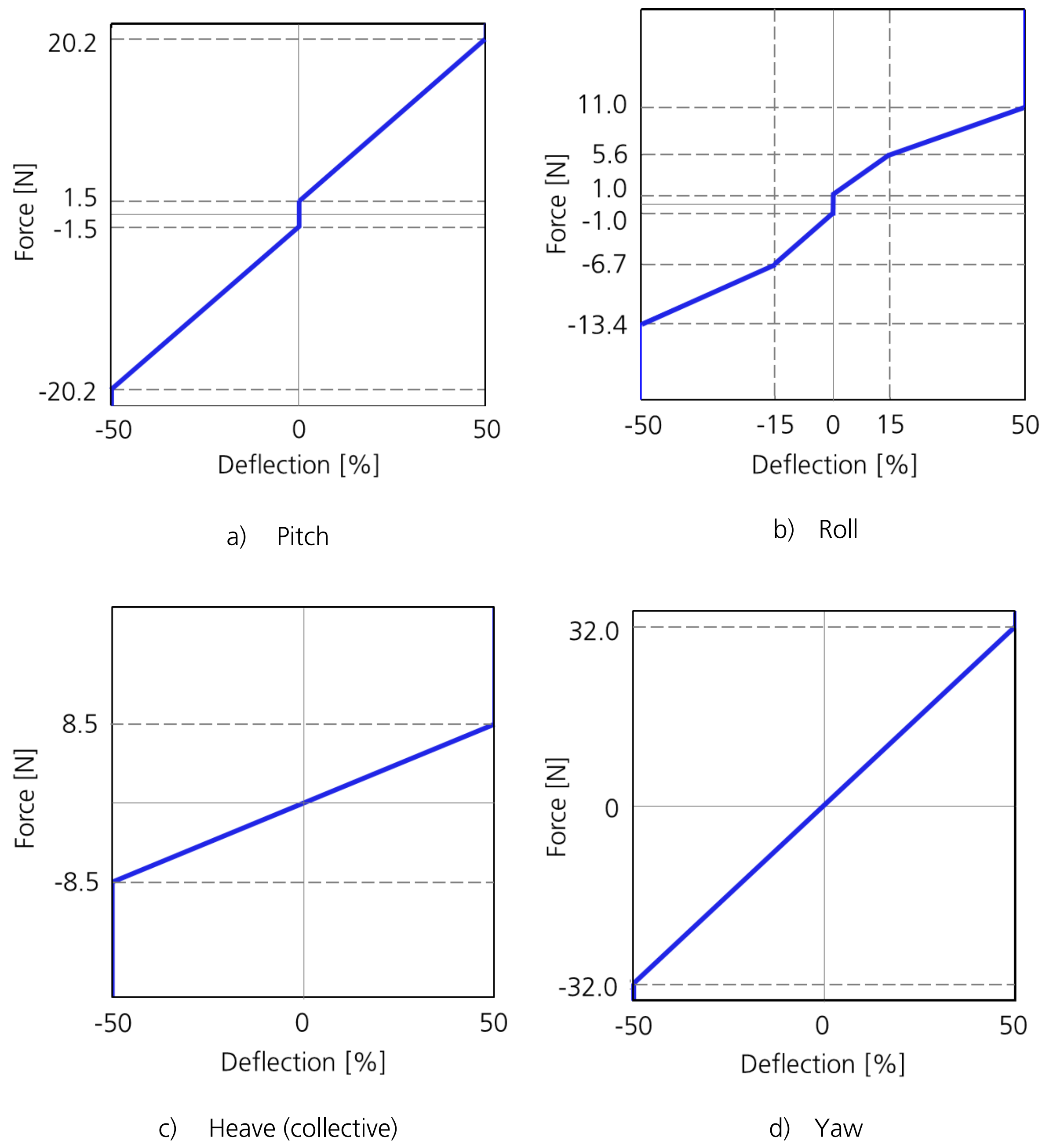


Figure 4.16: Force-deflection curves for pitch, roll, heave, and yaw axis

The present work noticeably differs from the reference one in [33] due to the lower control travel, and greater dynamic parameters (natural frequency and damping). Regarding the control travel, it was found during the tests that the active hard stop was more accurate than the physical limit imposed by the hardware. Therefore, the control deflection limits were reduced and fixed at 17 degrees, as presented in Figure 4.17 and Figure 4.18. Since the pedals are used to control the yaw axis, the term r_{FRP} is replaced by r_{RP} in Figure 4.18, which is the pivot arm relative to the reference point for application of force through the pilot's feet.

Regarding the dynamic parameters, the trend towards greater values confirms the findings in [38]. According to this work, there is a tendency for improved handling qualities ratings (HQR) with increasing natural frequency. Moreover, well damped inceptor is important to apply precise small inputs around trim [38].

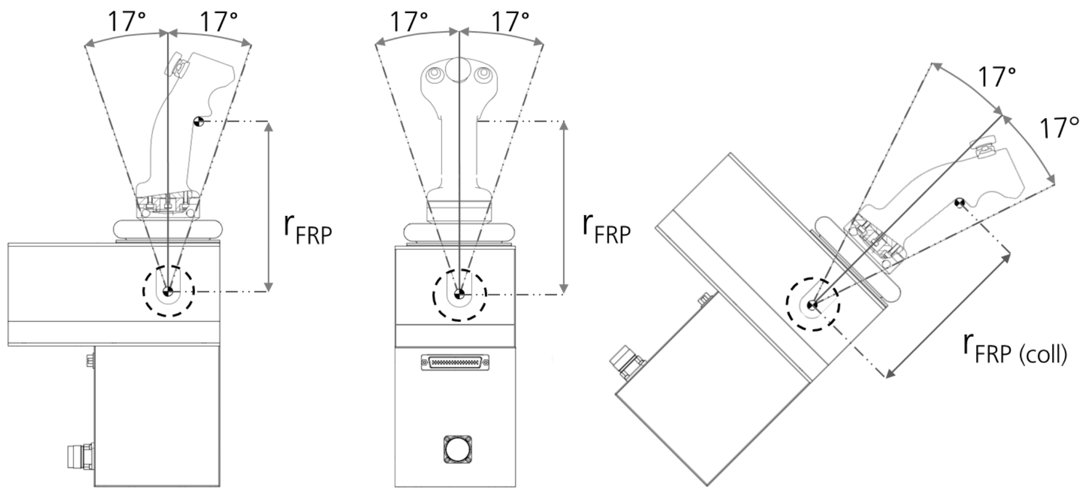


Figure 4.17: Hard stop values for pitch (left), roll (middle) and collective (right)

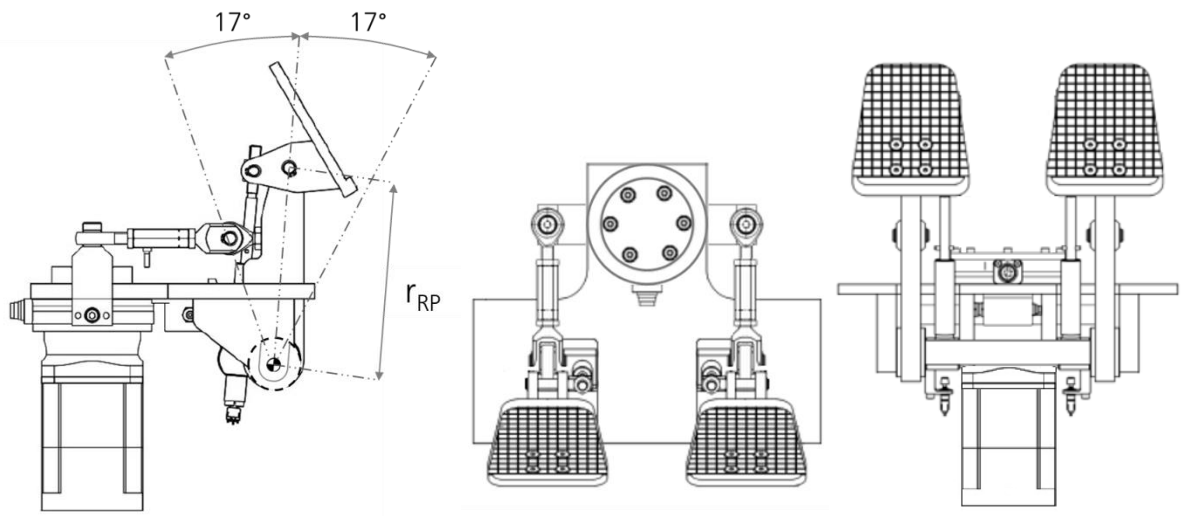


Figure 4.18: Hard stop value for pedals in lateral view (left), upper view (middle) and front view (right)

4.3.5 Trim System

The programmable nature of AIS allows for the development of a unique trim system for the decoupling system. The need for exclusive trim follow-up, beep trim, and force trim release relies on the fact that different logics are required depending on the couple/decouple condition.

Figure 4.19 shows a block diagram to provide trim prioritization of one control station, which is the flight instructor pilot in this example. If the inceptors are coupled, the upper input in switch 2 is selected. The trainee pilot can modify the trimmed position in both control stations, which is achieved by the selection of the upper input in switch 1. However, when the flight instructor uses the trim system, the middle input does not satisfy the criterion (higher than zero), because the *Not* block is false. Therefore, the switch 1 is placed in the lower input, providing priority for the flight instructor to determine the trim control position output in the inceptors of both pilots. In the case of deactivation of one pilot or uncoupled controls, the pilots only have the capability to adjust the trim position in their respective control cabin, without interfering in the other pilot setting.

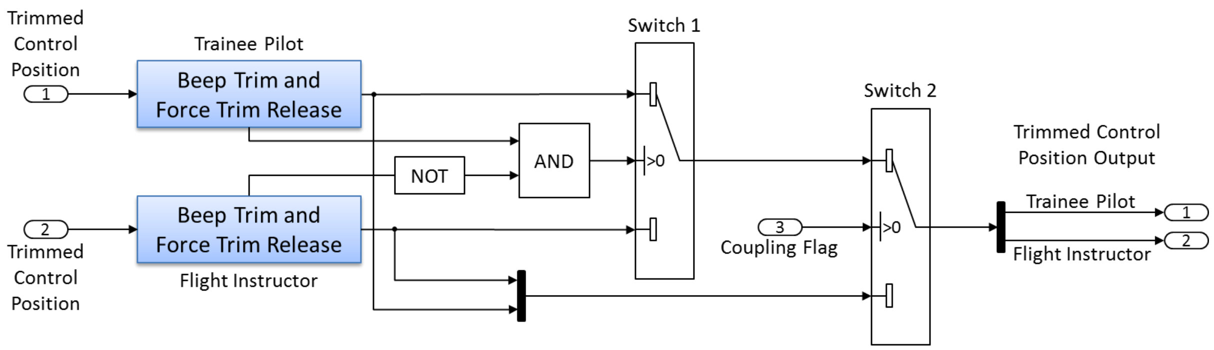


Figure 4.19: Trim prioritization of the flight instructor in coupled inceptor condition

An additional logic is required when the inceptors are commanded to recouple and there is divergence of the trim settings. In this case, the inceptors of the deactivated pilot should move towards the trimmed position of the active pilot. The pilot flying should always be the master trim reference position, in order to avoid interference in the inceptor position during the recoupling phase. A delay function is applied during the repositioning, so the inceptors are considered coupled only when they are practically in same position (tolerance of ±2%).

4.4 Concluding Remarks

The main topics discussed in this chapter are:

- The variable electronic inceptor system was developed to analyze the influence on the situation awareness and on the takeover control maneuvers.
- The active technology can assist pilots according to the theory of the HMC, since machine and human can combine efforts to achieve common goals. The variable inceptor coupling is implemented as a decision support system, which provides control authority to the pilots, but influences the inceptor coupling in case of control interference.
- Four inceptor coupling configurations were developed based on specific control laws: configuration 0 (uncoupled), 1 (coupled), 2 (coupled including automatic decoupling), 3 (coupled including manual decoupling).
- Two tactile cues are triggered in case of automatic decoupling: a force fading function (i.e., Counter Force) and a stick shaker in cyclic lever (namely, Cyclic Shaker).
- A dedicated warning system including visual and aural aids is developed based on design considerations of aviation guidance documents.
- The static and dynamic parameters of the force control mechanical characteristics for all inceptors (cyclic, collective and pedals) were defined and are listed herein. The calibration of the inceptors was the first step for the definition of the feel characteristics.
- Logics to trim follow-up, beep trim, and force trim release were developed due to the fact that different logics are required depending on the couple/decouple condition.

5 Experimental Setup and Methodology

This chapter presents the experimental setup, including the simulation environment and the helicopter model. Moreover, the research methodology for the evaluations is introduced.

5.1 Experimental Setup

5.1.1 Simulation Environment

Investigations were conducted in a ground-based helicopter simulator for dual pilot cockpit (Figure 5.1) at the Institute of Flight Systems of the DLR. The simulation platform, entitled "2 Pilot Active Sidestick Demonstrator" (2PASD), actuates in a pseudo real-time MATLAB/Simulink [99] environment. The test rig is a laboratory environment to prototype active inceptor functions and to validate pilot assistance systems in early stages of design. The structure of the new facility was developed featuring two control stations to provide the ability to conduct evaluations for dual pilot rotorcraft operation.

Before the evaluations, an anthropometric analysis guided the assembly of the mounting frames and the design arrangement, as illustrated in Figure 5.2. The reference values for the seat and the armrest is based on DLR's Air Vehicle Simulator (AVES) simulator [115], which contains a replica of the EC135 ACT/FHS cockpit.

Figure 5.1: Dual Pilot Active Sidestick Demonstrator - 2PASD

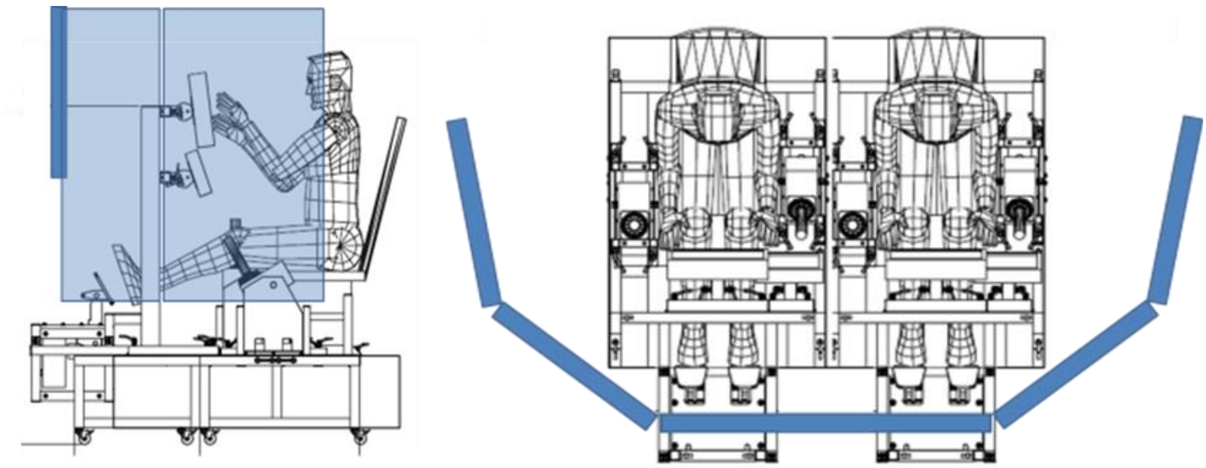


Figure 5.2: Anthropometric analysis in lateral (left) and upper view (right)

The modular concept allows the customization of different ergonomics patterns and anthropometric sizes, due to the extensive position options of the seat, pedals and monitors. The two pilot stations remained in side-by-side cockpit design for the tests.

The control loading system is equipped with four identical active sidesticks and two pedal modules. The sidestick supports are built to maintain the collective lever in neutral position at 45° related to the cyclic, as can be seen in Figure 5.3.

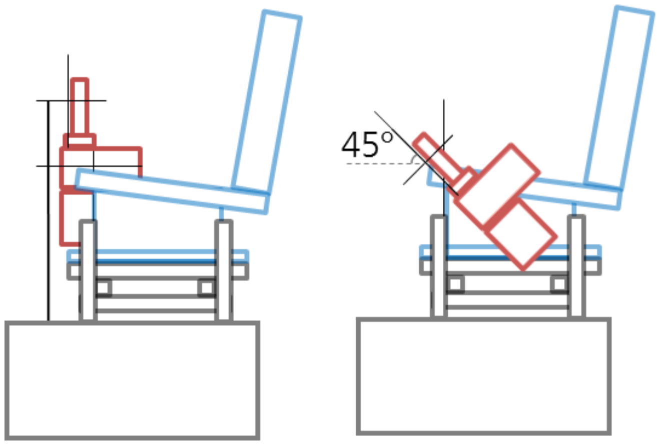


Figure 5.3: Cyclic and collective lever position related to pilot seat

The enabling simulation infrastructure of the 2PASD facility is the 2Simulate [116], an overall simulation framework to assist on the integration of model and simulation components. This software can modify and extent the predefined functionalities and reference model structures of the sidestick model following.

The 2PASD hardware architecture is presented in Figure 5.4. The user operates the simulation through the control center software in the development computer. The commands are sent to the interface computer, which establishes the communication with all the necessary parts of the simulation facility.

The system control module (SCM) computer is responsible for the accurate representation of the force-feel characteristics of the active flight controls. The inceptor feel data are transferred directly to the control loading system actuator units via CAN bus [117]. The inceptor coupling is achieved through the SCM data transfer, which are managed by the logics of the variable inceptor coupling model within the interface computer.

The sidesticks includes suitable plug-connection as part of grip-interface. The provision on the communication bus enables the operation of 14 digital inputs (switches), making possible the functions of grip buttons, beep-trim and 4-axis switch.

In the 2PASD visual system, three graphic desktops manage the computational power needed to generate the image outputs in five 55 inches monitors and the four touchscreen displays of 43 cm (17 inches). The software 2Indicate implements instrument panels and simulation control device on displays in both pilot stations [116], [118]. Table 5.1 presents the specifications of the visual system. Figure 5.5 shows the field of view (FOV) of the 2PASD simulator considering the middle point between the pilot seats as the reference.

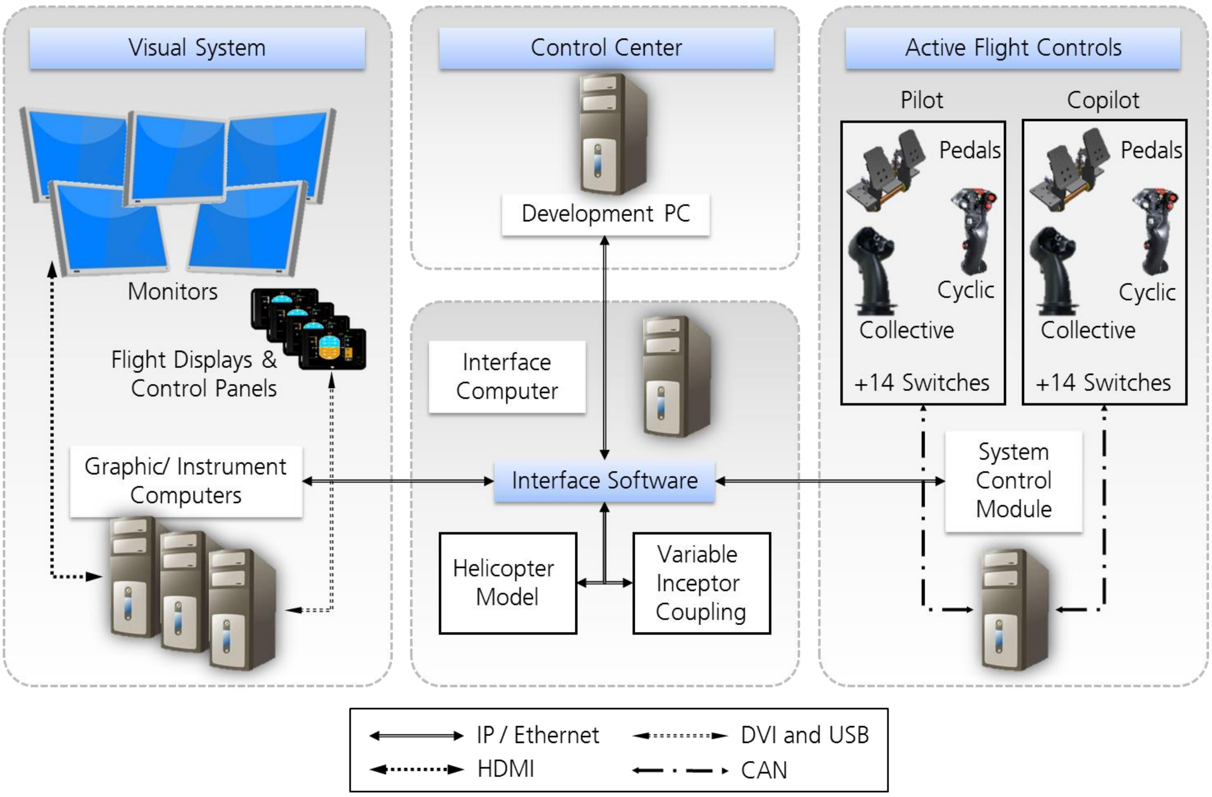


Figure 5.4: 2PASD Hardware architecture

Table 5.1: Settings of 2PASD visual system

2PASD	Description
Simulator Type	Ground-based (Rack type)
FOV - Horizontal	±100°
FOV - Vertical	+10°; -40°
Image generation	5 monitors LED 55 inches
Native Resolution	1280 x 1024

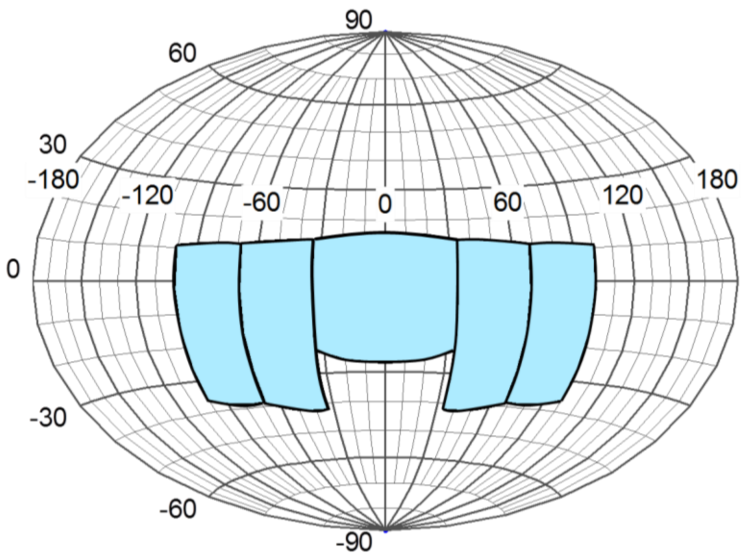


Figure 5.5: 2PASD field of view

5.1.2 Helicopter Model

The response type of the helicopter tested is attitude command attitude hold (ACAH) in pitch and roll axes, and rate command (RC) in yaw and heave axes. The helicopter modeled is based on the ACT/FHS (Figure 5.7), a highly modified version of the EC 135 used by DLR as an in-flight simulator for research purposes [119]. For this reason, its performance and qualities do not reflect operational variants of the rotorcraft type. ACT/FHS is a twin-engine, light helicopter with a bearingless main rotor and fan-in-fin tail rotor. In addition to mechanical controls, the ACT/FHS is equipped with full authority digital FCS using fly-by-wire and fly-by-light technology [119].

The helicopter dynamics are derived by system identification using flight test data [120]. As depicted in Figure 5.6, the control laws are modeled through an iterative process, including design, simulator testing, and flight testing [121]. Typically, new or unexpected observations in the flight test drive the continuous development of the simulation model.

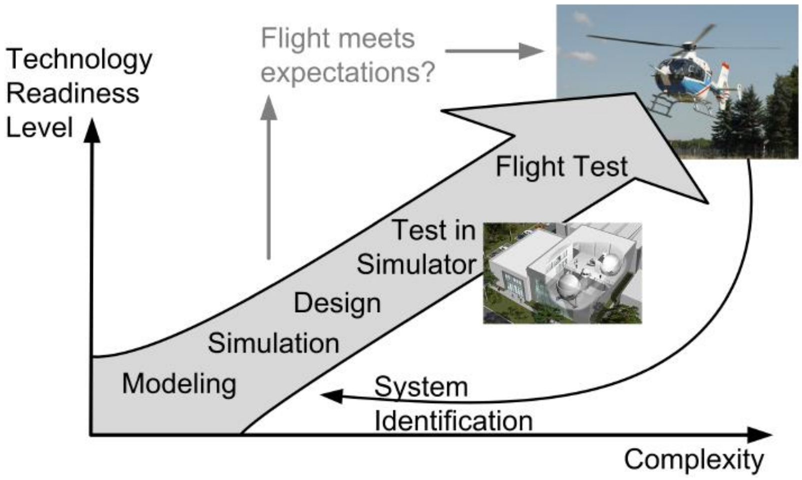


Figure 5.6: Typical process of simulation optimization by test flight data [121]

The dynamic helicopter model consists largely of a physically based mathematical description with 11 degrees of freedom (DoF) adapted for real-time simulation. The formulation of the model begins with the basic 6-fuselage DoF by applying Newton's law and Euler's equations for rigid body dynamics [120]. The derivation of the differential equations of rigid body motion can be found in [122, p. 92]. The general motion of the helicopter relates the applied forces and moments to the resulting translational (surge, heave, and sway) and rotational (pitch, roll, and yaw) accelerations. The classical 6-DoF rigid body model is incrementally extended by additional high-order dynamic effects to cover fuselage-main rotor interactions [123]. To this end, the model accounts for longitudinal and lateral rotor flapping [124], dynamic inflow [125], and the rotor lead-lag motion [126], [127]. The increasing complexity process resulted in the 11-DoF model used in this thesis. A detailed derivation of the equations of the 11-DoF model is described in [120].

As the aerodynamic effects of helicopters vary with airspeed, a set of linear identified models is needed to cover the whole flight envelope. Therefore, a quasi-nonlinear simulation that stitches these linear models together is applied to generate of a full-envelope simulation [128]. In addition, inverse simulation improves the linear model accuracy at a certain operating point by modeling additional non-physical transfer functions. It is achieved through the relation of the output errors to the control inputs, so the output can fit the predicted measurements. Further information about the model stitching and inverse simulation techniques are presented in [123], and [129]. The augmented and stitched model shows high simulation fidelity. Even the challenging nonlinear and unstable air resonance mode of the AC135 ACT/FHS is modeled. In several flight control design studies, the augmented and stitched model has proven its high fidelity, meaning that almost no iterative feedback control tuning is needed to arrive at high bandwidth control systems. Due to the high fidelity, the results presented hereafter should be very close to future flight tests with the ACT/FHS.

Handling Qualities – Predicted Criteria

An analysis of the helicopter model responses to pilot's open loop inputs was performed to support the investigation of the handling qualities. To evaluate handling qualities for rotorcraft, the most comprehensive set of requirements is provided by the US Army's ADS-33E [114]. The requirement criteria provide quantitative benchmarks which is valuable for diagnosing the cause of an eventual deficient performance [114]. There are three predicted levels of handling qualities. The rotorcraft is considered level 1 (i.e., capable to perform intended missions without limitation) if meets the Level 1 standards for all of the criteria [114]. Improvements are desired in case of Level 2, but the deficiencies do not prevent the mission completion. Level 3 impacts the flight task aim and improvements are mandatory, however the helicopter could show such characteristics in special conditions, as emergencies.

Figure 5.7: The Flying Helicopter Simulator (FHS), an EC-135 type [120]

Appendix A.1 describes the criteria analyzed, which are bandwidth, dynamic stability, attitude quickness, height response, torque, pitch-roll coupling and yaw-collective coupling. The parameters are plotted against the predicted levels of handling qualities, along with the inputs and values, as shown in the Appendix A.2. The results are summarized in Figure 5.8. The criteria limits are specified for fully attended operation[1] requirements.

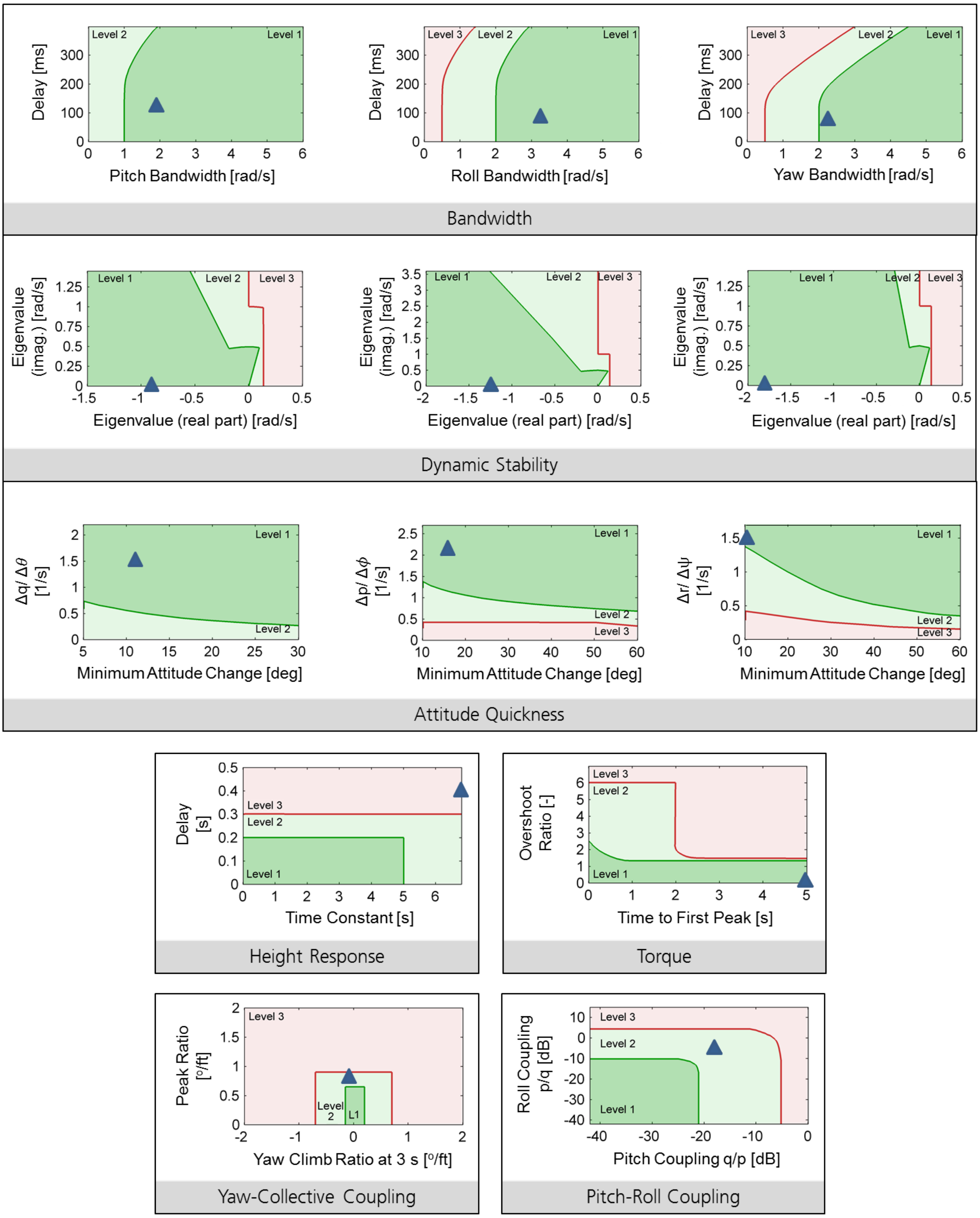


Figure 5.8: Handling qualities evaluation of the helicopter model

[1] The pilot flying the rotorcraft can devote full attention to attitude and flight path control.

The helicopter is mostly level 1 HQ. Violation of the level 1 requirement can be identified for height response (level 3), pitch-roll coupling and yaw-collective coupling (level 2). Thus, it is expected a degradation in handling qualities during the tasks [114], which may lead to increased pilot workload to achieve the maximum (desired) performance. Conditions of high workload are important to the present discussions, because the force feedback of the inceptors can be a valuable information resource in such conditions. Therefore, the predicted levels of handling qualities indicated in this analysis are judged to be adequate for the evaluations.

5.2 Methodology

The research analyzes the controllability problem during takeover control maneuvers. One main aspects of this problem is the uncertainty regarding the ability of active coupled inceptors to provide awareness to the FI to monitor the performance of the trainee pilot in helicopter flights. Moreover, the second significant aspect of the problem is the impact of a decoupling system on the control deflection and the helicopter attitude during takeover control maneuvers using electronically coupled inceptors.

The evaluation of these two problematic aspects is structured in three parts, which are shown in Table 5.2 and described here. Each evaluation part is linked to one aspect of the scientific questioning (SQ), which are valuable to answer the main research problem, regarding the influence of the electronically coupled active sidesticks on the takeover control maneuvers in low-level flight.

Table 5.2: Evaluation plan and methodology

Evaluation	Analysis Scope	Criteria	Sampling
Situation Awareness Test (SQ1)	Ability to emulate mechanical linkage and influence on situation awareness	Measurement of the situation awareness	3 test pilots
Inceptor Decoupling Development (SQ2)	Influence of force threshold and fading logic on flying qualities	Assignment of ratings for transient, oscillations and handling qualities	4 test pilots
System Validation (SQ3)	Assess the control and attitude transients, pilot workload and pilot acceptance during takeover control maneuvers	Measurement of control and attitude transients, pilot workload and pilot acceptance	5 Pilots (3 test pilots)

The first part examines the ability of the electronic system to provide understandable and deterministic feedback to the pilots to predict near-future states of the helicopter. The second part is focused on the development of an automatic decoupling system in case of pilot overriding action to takeover control. The third part investigates the attitude and control transients using inceptor decoupling systems, in order to ascertain the consequences of this novel function to the helicopter controllability. All parts are focused on hover and low speed ranges, due to the characteristics of the LOC accidents during takeover control maneuvers.

5.3 Concluding Remarks

The main topics of this chapter are:

- The simulation platform was developed to the present thesis, requiring anthropometric analysis of the cockpit, programming of the control loading system, and implementation of the interface software within the simulation hardware architecture.
- The helicopter model consists of a physically based mathematical description of a model with 11 DoF adapted for real-time simulation. The dynamic model is based on flight data of the ACT/FHS, a light helicopter with a bearingless main rotor.
- An analysis of the helicopter model responses to pilot's open loop inputs was performed to support the investigation of the handling qualities. The predicted criteria of the ADS 33E were utilized. The helicopter is HQ level 1 for nine criteria, but is HQ level 2 for the pitch-roll coupling and yaw-collective coupling, and HQ level 3 for height response. These characteristics can influence the performance of the pilots during the tasks, because the pilot might have additional effort to compensate the items that violated of the level 1 requirement. Conditions of high workload are important to the present discussions, because the force feedback of the inceptors can be a valuable information resource in such conditions. Therefore, the predicted levels of handling qualities indicated in this analysis are judged to be adequate for the evaluations.
- The methodology is comprised of three piloted evaluation parts. In the first part, the influence of the electronic inceptor coupling on the situational awareness of the pilot monitoring is analyzed by three test pilots. This is the first part of the discussion, because the ability of the system to provide understandable and deterministic feedback is crucial to perform successful takeover control maneuver.

- The second set of evaluation consists in the development of the automatic decoupling function. The investigation seeks to provide information about the influence of this novel function on the pilot controllability. Therefore, the flying qualities after the inceptor decoupling are analyzed against standardized rating scales with the help of 4 test pilots.
- In the last evaluation part, five pilots assigned subjective ratings for pilot workload and pilot acceptance for the inceptor system including decoupling means. The permanently coupled inceptor is also included for comparison. A quantitative analysis of the control and attitude transients in takeover control maneuvers is performed to support the subjective ratings.

6 Situational Awareness Test

The chapter presents the evaluations performed for the situational awareness test, in which the inceptor coupling configuration 0 (uncoupled) and 1 (coupled) are analyzed. The description of the configurations can be found in subsection 4.3.1.

6.1 Test Aim

The aim of this evaluation is to analyze the influence of the electronically coupled active sidesticks on the SA of the helicopter FI pilot. To this end, the following topics are attested:

- Comparative assessment of the coupled and uncoupled sidesticks in relation to the ability to provide awareness of the trainee (PF) inputs
- Comparative assessment of the coupled and uncoupled sidesticks in relation to the ability to provide overall SA

The ability of the coupled inceptor to provide understandable and deterministic feedback to the pilots to predict near-future states of the helicopter is an essential question per se. Furthermore, it is also crucial for successful takeover control maneuvers, because it can be taxing to detect errors and intervene timely to avoid an unsafe situation without a shared understanding of the actions on control.

The inceptor coupling configuration 1 (i.e., permanently coupled sidesticks) is likely to provide greater SA capability compared to configuration 0 (i.e., permanently uncoupled sidesticks). This hypothesis is supported by the information described in subsection 3.1, which addresses the force feedback significance. Additionally, the inceptor coupling increases the predictability of flight states, as discussed in subsection 3.2. High pilot workload environments can substantially raise the importance of the inceptor coupling due to the limited ability of pilots (as human operators) to recognize the available information, which is also discussed in subsection 3.2.

However, the validation of this hypothesis can be considerably affected by the quality of the inceptor synchronization and by the task constraints [20]. Since the impact of this type of inceptor coupling to the SA has not been measured yet, a comparative evaluation between permanently coupled sidesticks and permanently uncoupled sidesticks is employed.

6.2 Method – SAGAT

The objective measure of SA is achieved through the Situation Awareness Global Assessment Technique (SAGAT), as described by Endsley [130], [131]. The method employs periodic, randomly-timed freezes in a simulation scenario during which all of the pilot's displays are temporarily blanked [132]. A series of queries are provided to the pilot to assess his or her knowledge of what was happening in the simulation at the time of the freeze within operationally determined tolerance zones [132]. The queries typically cover SA elements at all three levels of SA (perception, comprehension and projection) [133], as described in subsection 3.2 and Figure 3.2.

The SAGAT offers an objective, unbiased measurement of pilot SA, and no subjective judgments is required [134]. The method collects SA diagnostic information throughout activities, which removes the various problems associated with collecting post-trial and subjective SA data (e.g., correlation of SA with performance, poor recall, etc.) [135]. It has been frequently asserted that the technique relies on memory, and thus might not provide a true reflection of operator SA [132]. However, it has been found that subjects are able to report their assessments for as long as 5 to 6 minutes during SAGAT freezes without memory decay being a problem [131].

The SAGAT is the most widely used approach, and also is the technique with the most associated validation evidence [134]; [135]. The method was developed specifically for use in the aviation field, although it has consistently demonstrated reliability and validity[1] in a number of domains [135]. The main disadvantages of the SAGAT are the need for extensive preparation, access to complex simulation facilities, and ability to stop and restart simulation [134]. Nonetheless, all these difficulties were overcoming by the present study (see experimental setup in subsection 5.1). It should be noted that the technique may be intrusive to primary task, thus it is not well suited to actual operations.

[1] According to Salmon et al. [135], reliability refers to the degree to which the measure will generate the same data when measuring SA repeatedly under the same conditions. Validity refers to the accuracy of the method in terms of the extent to which the technique is actually measuring SA, and not some other construct.

6.3 Evaluations

6.3.1 Experimental Scenario

The transverse repositioning task was conceived to analyze the SA in a dual pilot helicopter cabin. The interaction between FI and trainee pilot is the most representative and challenging case, due to the need of the FI to constantly monitor the trainee performance.

The task is illustrated in Figure 6.1 and fully described in Appendix B.1. The movement of the helicopter in diagonal manner (45° to the reference line) imposes the challenging of combining two axes inputs in the cyclic lever (longitudinal and lateral). The trainee pilot seat is placed on the opposite side of the helicopter translation, which makes visual monitoring of the trainee pilot inceptors difficult.

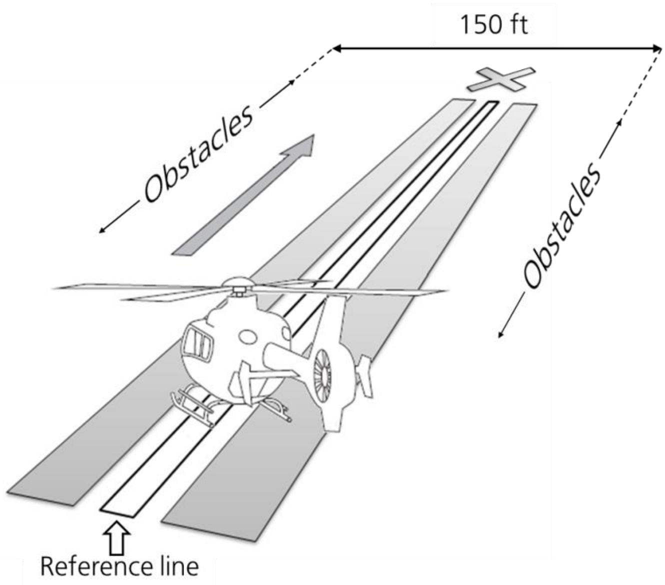


Figure 6.1: Transverse repositioning task

The trainee pilot initiates the tasks, observing the target performance (15 kt, 50 ft above ground level - AGL, heading 230°, and obstacle clearance of 20 ft). As regularly performed in training flights, the FI applies the follow through technique (i.e., following closely the inceptor movements by resting hands on control). The flight instructor helps the trainee pilot by interfering on control if the flight performance is out of the tolerance limits (as specified in Table B.1). Hence, the FI shall identify the current flight parameters and inceptor inputs, correlate the parameters to the tolerances, project nears future of the helicopter states, and interfere on control, when applicable.

Figure 6.2 shows the scenario for the transverse repositioning MTE. The obstacles consist in trees, buildings, bridges, traffic lights and cars. The grass in the middle of the roads is used as the reference line.

Figure 6.2: Transverse repositioning task in city scenario

6.3.2 Procedures

Three pilots participated in the SAGAT survey, and their flight experience is defined in Appendix C.1. Pilots A, B and C are test pilots, flight instructors and have sidestick experience. The test pilots (referred to throughout as the FI) act as instructor pilots during the completion of the transverse repositioning MTE.

During the SA test, FIs performed 6 trials to each coupling type (coupled and uncoupled inceptors), alternating after each trial. The initial mode was also changed for each pilot. The coupled and uncoupled inceptor configurations remained constant during the same experimental trial (no decoupling).

A summary of the briefing presented to the FI is included in Appendix D.1.1. Before the trials, a practice session of 10 min was provided. One test pilot (hereafter trainee pilot) performed as the pilot flying. The trainee pilot could activate one button in the collective lever to halt the simulation trial at the point of interest, according to the queries of the questionnaire. The moment of the simulation freeze was unknown by the FIs. The control center operator, positioned behind the pilots' seat, was responsible to turn off the displays of the visual system. Each trial lasted two to five minutes until the simulation is halted, when the FI answered a questionnaire including a series of queries.

The SAGAT queries were developed based on a cognitive task analysis, which arranges the major goals and corresponding major decisions in a typical training flight. The goal-directed task analysis for the SAGAT survey is described in the Table D.1. In general, during the training flight, the FI monitors the trainee performance and avoids accident, besides additional duties (like communication and navigation management). In order to reproduce the additional duties, a subtask is introduced. It consists in observing lights that are eventually illuminated during 5 seconds in the warning panel. The proposed scenario is considered demanding due to the need to accomplish multiple simultaneous tasks.

The SAGAT survey is comprised of 15 queries, as outlined in the Table D.2. The queries cover the following SA requirements:

- Geographical SA: location of own helicopter, terrain features, position relative to scenario features, and path to desired locations
- Spatial/Temporal SA: heading, speed, height, and projected flight path.
- System SA: inputs on inceptors, and lights on warning system
- Environmental SA: obstacles to avoid, and flight safety

Due to time constrain, only eight out of 15 queries could be applied twice. Therefore, each pilot answered 23 queries, which were distributed in six questionnaire types (subsection D.1.4). The order of the questionnaire types was randomly selected.

6.3.3 Statistical Analysis – McNemar Exact Test

The SAGAT answers are binary response variables. In other words, the answers to the queries are either right or wrong, which are coded in values of 1 and 0, respectively. The test design is called within-subjects (or matched pairs), since the same pilots tested both inceptor types under the same conditions. This characteristic increases the chance of detecting differences (higher power), because it removes the variation between users.

The McNemar exact test is used to determine whether there is a significant difference between dichotomous variables [136]. This hypothesis test is a non-parametric (or distribution-free) inferential statistical method, since there is no assumption about the probability distributions of the variables being assessed. Table 6.1 shows the nomenclature used to represent the cells of the 2×2 table for this type of analysis.

The primary test metric is the number of trials included in the discordant pairs, i.e., the trial that the participant answered correctly for one design and incorrectly for another. The statistic calculates if the proportion of discordant pairs (cells b and c in Table 6.1) is greater than what is expected from chance alone. For this type of analysis, the chance is set to 0.5. If the proportion of discordant pairs is different from 0.5 (higher or lower), than we have evidence that there is a difference between designs.

Table 6.1: Nomenclature for McNemar exact test

		Coupled Inceptors [answers]		
		Right	Wrong	Total
Uncoupled Inceptors [answers]	Right	*a*	***b***	*a* + *b*
	Wrong	***c***	*d*	*c* + *d*
	Total	*a* + *c*	*b* + *d*	*N*

The observed proportion is tested against the hypothesized proportion of 0.5 through the nonparametric binomial test, which uses the following probability formula [137]:

$$p(x) = \frac{n!}{x!\,(n-x)!}p^x(1-p)^{(n-x)} \tag{6.1}$$

where

x is the number of positive or negative discordant pairs (cell c or cell b, whichever is smaller),

n is the total number of discordant pairs (cell b + cell c)

p = 0.5

The term $n!$ ("n factorial") is defined as $n \times (n-1) \times (n-2) \times \ldots \times 2 \times 1$.

The *p*-value refers to the probability that the difference between two means is really 0. The hypothesis of no difference is referred to as the null hypothesis. A low *p*-value means the null hypothesis is unlikely to be true, therefore the research hypothesis tends to be true (meaningful difference between the inceptor configurations).

6.4 Results and Discussion

6.4.1 Results

Each pilot answered 23 queries for each active inceptor design (coupled and uncoupled). The result of the SAGAT survey for each query is presented from Table E.1 to Table E.3.

Figure 6.3 shows the percentages of correctness to the SA queries per pilot. The number of correct answers of all three pilots using the coupled configuration was consistently higher compared to the uncoupled counterpart. The correct answers for the coupled design were 13% to 26% higher than for the uncoupled, as indicated in Table 6.2. On average, there was a difference of 19%.

A statistical analysis is employed to determine whether the difference of 19% (or 13 questions) represents a statistically significant reduction. To this end, the McNemar exact test analyses the proportion of discordant pairs in paired nominal data, as highlighted in bold in the Table 6.3.

Table 6.2: Correct answers to SAGAT survey – overall questions

Active Inceptor Type	Total Number of Queries	Test Pilots			
		Pilot A [%, (value)]	Pilot B [%, (value)]	Pilot C [%, (value)]	Total [%, (value/total)]
Coupled	23	96 (22)	70 (16)	87 (20)	84 (58/69)
Uncoupled	23	78 (18)	57 (13)	61 (14)	65 (45/69)
Difference	-	18 (4)	13 (3)	26 (6)	19 (13/69)

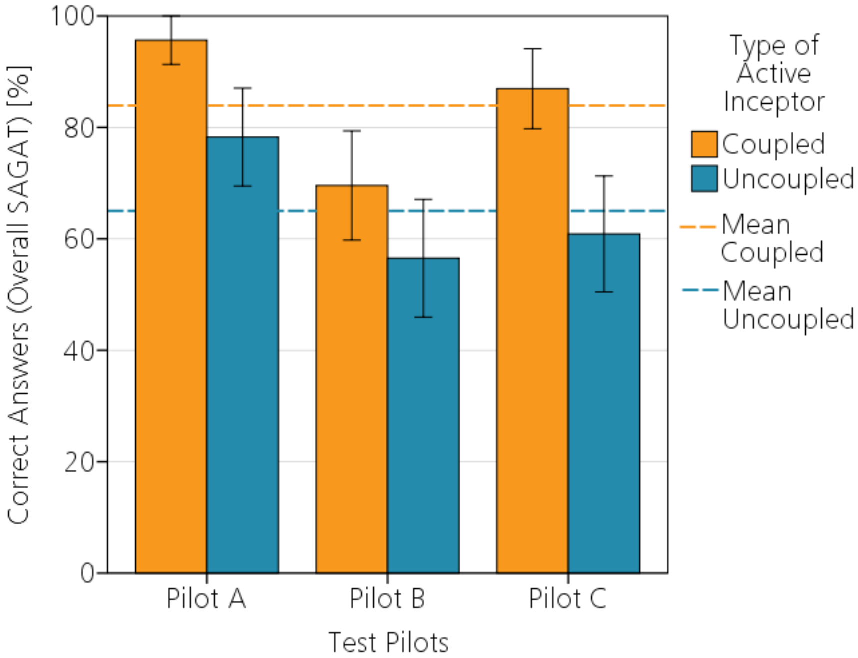


Figure 6.3: Correct answers to SAGAT survey – overall questions (bars ±1 standard error)

In this case, according to the equation (6.1), the null hypothesis was rejected, since the statistical significance level (i.e., exact *p*-value) is equal to 0.002, which is less than the cutoff level for significance (p = 0.050). It means that the variation in the proportion of SA correct queries using coupled and uncoupled inceptors is a statistically significant. Thus, the probability to achieve such proportion of discordant pairs (15 versus 2) if there really is no difference between the inceptors design is 0.002. In other words, there is about 99.8% sure that the coupled inceptor configuration provides higher SA than uncoupled inceptor configuration.

Table 6.3: McNemar exact test – overall SAGAT questions

		Coupled Inceptors [answers]		
		Right	Wrong	Total
Uncoupled Inceptors [answers]	Right	*43*	***2***	*45*
	Wrong	***15***	*9*	*24*
	Total	*58*	*11*	*69*

Questions regarding Trainee Pilot Inputs

Out of the total 23 queries, 4 inquiries are dedicated to investigate the awareness of the FI regarding the trainee pilot inputs. These 4 queries are the following two sentences, which were answered twice per pilot (Table D.2):

- Enter the axis/direction of the trainee pilot input in the last 3 s
- Enter the recommended control input to maintain the helicopter within the tolerance of the task performance

The trainee pilot applied constant force to a specific point in the flight control envelope in the last 3 seconds prior a simulation freeze. The first query is a simple identification of the pilot input. The second query requires the understanding of the impact of the input applied. For instance, if the helicopter is flying in the target height (50 ft AGL) and the collective lever is moved downwards, the FI should recommend an input in the collective lever upwards to stay within the performance tolerance. In the coupled configuration, the force feedback can convey the information necessary to answer this question. In the uncoupled inceptor case, FI shall answer based on visual cueing, like helicopter attitude changes and panel information (PFD).

The percentages of correctness of the SA questions addressing inputs of the trainee pilot are shown in Figure 6.4 and Table 6.4.

Pilot A was the only pilot to correctly answer at least one SA query using the uncoupled inceptors. In total, only three out of 12 possible correct answers were verified. All pilots indicated that visual cues did not compensate the force feedback provided by the coupled inceptors.

Conversely, there is a single wrong answer using coupled inceptors concerning the same subject, which was made by pilot C. According to this pilot, the mistake was not caused by the inceptor coupling quality, but by the attentional limitations due to the high demanding task.

The ability of the coupled inceptors to provide awareness of the pilot flying inputs to the FI is attested statistically. Table 6.5 indicates the pairwise information used in the McNemar exact test. There is a statistically significant difference in the proportion of answers to the SAGAT survey regarding the trainee pilot inputs (exact *p*-value = 0.008).

Table 6.4: Correct answers to SAGAT survey – trainee input questions

Active Inceptor Type	Total Number of Queries	Test Pilots: Pilot A [%, (value)]	Pilot B [%, (value)]	Pilot C [%, (value)]	Total [%, (value/total)]
Coupled	4	100 (4)	100 (4)	75 (3)	92 (11/12)
Uncoupled	4	75 (3)	0 (0)	0 (0)	25 (3/12)
Difference	-	25 (1)	100 (4)	75 (3)	67 (8/12)

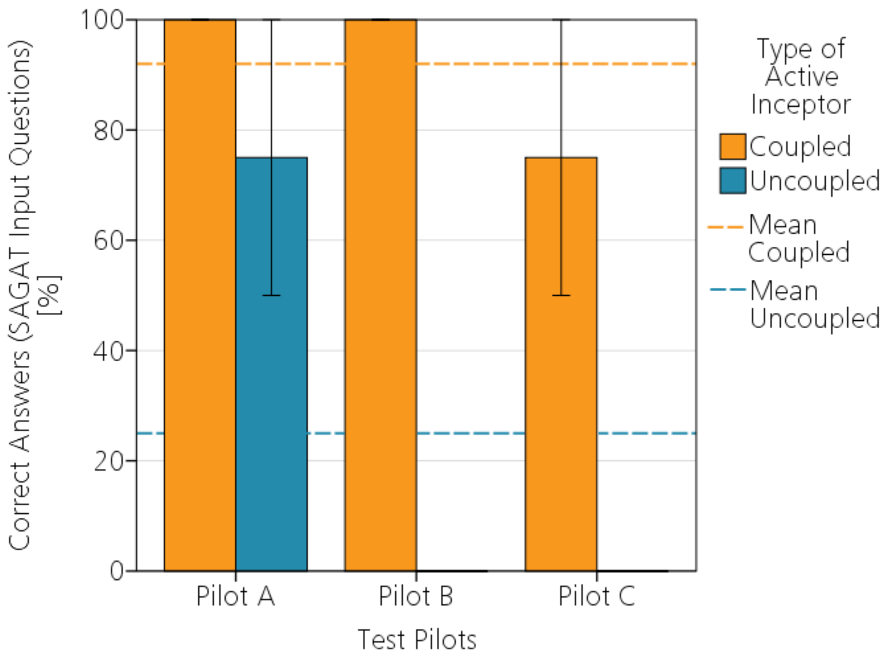


Figure 6.4: Correct answers to SAGAT survey – trainee input questions (bars ±1 standard error)

Table 6.5: McNemar exact test — trainee input questions

		Coupled Inceptors [answers]: Right	Wrong	Total
Uncoupled Inceptors [answers]	Right	*3*	***0***	*3*
	Wrong	***8***	*1*	*9*
	Total	*11*	*1*	*12*

SA Levels Results

The results on SAGAT queries are aggregated within SA levels (i.e., perception, comprehension, or projection). This approach verifies consistency between query response patterns at the selected level of SA. The topics of the queries for each level are:

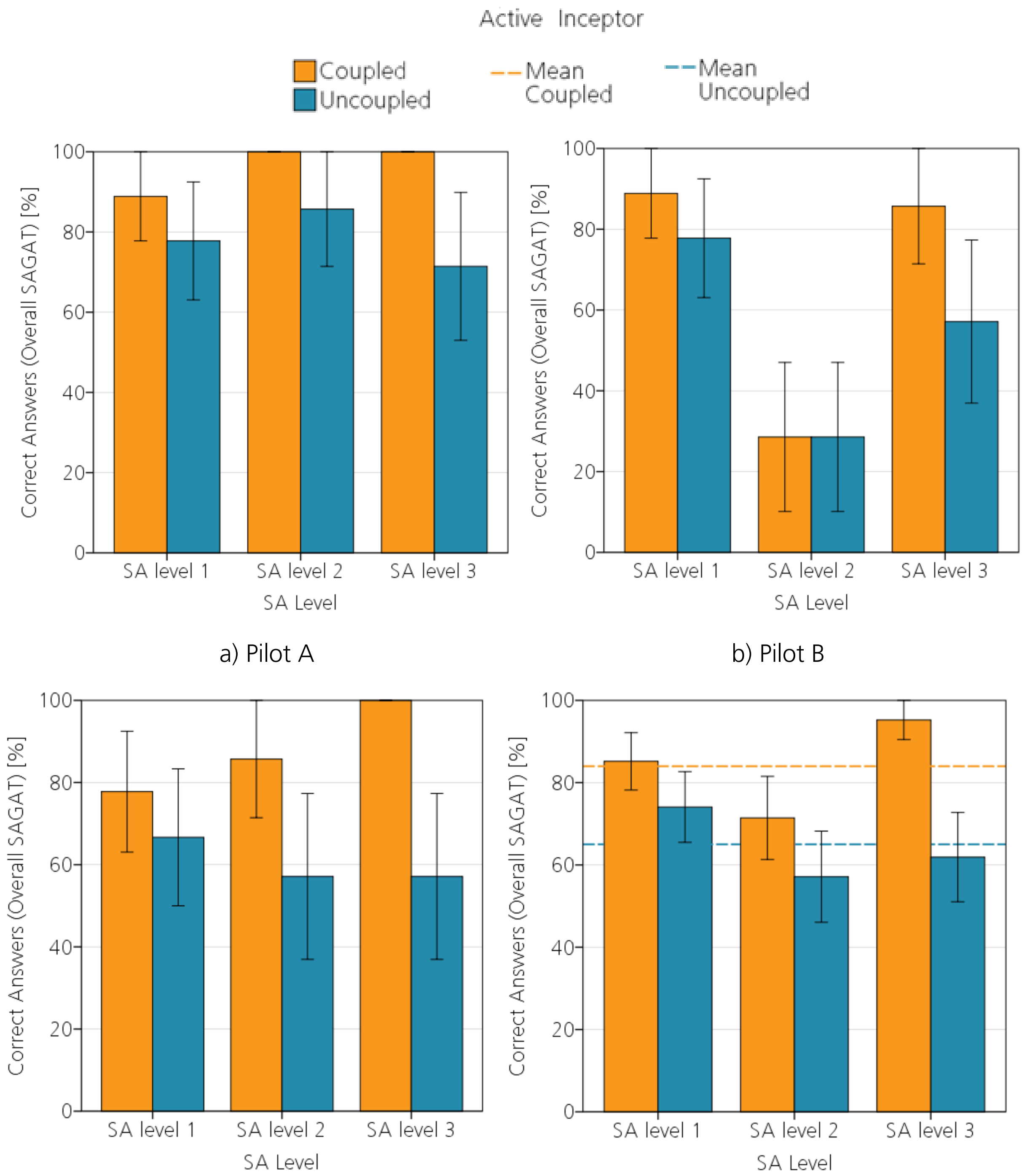
- SA level 1: current states (helicopter position, speed, height, heading, inceptor input, and light on warning panel)
- SA level 2: most critical obstacle, exceeded performance tolerance (speed, height, and heading), total lights illuminated
- Level 3: recommended input to maintain performance tolerance, future variations (helicopter position, speed, and height)

Table 6.6 presents the correct answers to SAGAT survey divided by SA levels. It can be noted a typical reduction in the number of correct answers of all SA levels when pilots flew the helicopter equipped with uncoupled inceptors, as can be seen in Figure 6.5d. The exception is the comprehension (level 2) of the pilot B, which performance was low (29%) and equivalent to both designs. After the test, pilot B declared that the number of parameters and subtasks was too high, so he deprioritized queries related to level 2 to have enough attentional capacity to execute other subtasks.

Table 6.6: Correct answers to SAGAT survey divided by SA levels

Active Inceptor Type	Situational Awareness Level	Number of Queries	Test Pilots			Total
			Pilot A [%, (value)]	Pilot B [%, (value)]	Pilot C [%, (value)]	[%, (value/total)]
Coupled	Level 1	9	89 (8)	89 (8)	78 (7)	85 (23/27)
	Level 2	7	100 (7)	29 (2)	86 (6)	71 (15/21)
	Level 3	7	100 (7)	86 (6)	100 (7)	95 (20/21)
Uncoupled	Level 1	9	78 (7)	78 (7)	67 (6)	74 (20/27)
	Level 2	7	86 (6)	29 (2)	57 (4)	57 (12/21)
	Level 3	7	71 (5)	57 (4)	57 (4)	62 (13/21)
Difference	Level 1	-	11 (1)	11 (1)	11 (1)	11 (3/27)
	Level 2	-	14 (1)	0 (0)	29 (2)	14 (3/21)
	Level 3	-	29 (2)	29 (2)	43 (3)	33 (7/21)

The higher difference between the inceptor designs is verified in the third level, which is the highest level of SA. Out of 21 queries, the pilots answered correctly 20 times using the coupled design, whereas this number reduces to 13 when the uncoupled inceptors are featured.



a) Pilot A b) Pilot B

c) Pilot C d) Total (3 pilots)

Figure 6.5: Correct answers to SAGAT survey divided by SA levels (bars ±1 standard error)

6.4.2 Discussion

The electronic emulation of mechanical controls (coupled inceptor configuration) was considered suitable to the task of monitoring the trainee pilot performance. In general, the pilots indicated that the electronic coupling of the active inceptors was alike to true mechanical linkage.

The main contribution of the SAGAT method is the possibility to quantify the contribution of the inceptor designs to the SA. Additionally, three main outcomes can be point out.

Firstly, the force feedback contributed to the FI's awareness regarding the trainee pilot inputs, which is expected, due to the information provided in subsection 3.1. This characteristic is meaningful to the ability of monitoring the performance of the pilot flying. For instance, the pilot A declared that "as an instructor, it is almost impossible to monitor control input without coupled controls." Thus, it can be stated that the visual cues (helicopter motion and information on PFD) cannot replace the force feedback provided by the coupled inceptor. Also, pilots considered the electronic coupling of the active inceptors alike the true mechanical linkages across the cabin.

Secondly, there is a striking correlation between the overall SA of the FI and the inceptor coupling type. The results indicate that the coupled inceptor configuration impacts positively on the SA in general when compared to the uncoupled configuration. For instance, pilots C failed to indicate the position of the helicopter related to the scenario, and pilot A ignored the lights on the warning panel, but only when flying with uncoupled inceptors. Pilot B asserted that uncoupled inceptors are "more mentally demanding." Pilots communicated that the monitoring task was negatively affect by the removal of inceptor coupling, since the flight predictability has decreased. The results of the statistical analysis corroborate the opinion of the pilots.

The third finding is related to the influence of the inceptor coupling on the ability to project future states of the helicopter (SA level 3). The greater discrepancy between the SA performances derives from this level. Researchers already found that a significant portion of experienced pilot's time is spent in anticipating possible future occurrences [138]. In the case of the coupled inceptor, the extra information conveyed by the force feedback can provide the anticipatory responsiveness, which is meaningful in flights near obstacles. Conversely, the lack of inceptor coupling may adversely affect the shared SA in a dual pilot helicopter cabin.

Taken together, these results indicate that the coupled inceptor configuration is an important feature to provide SA to the FI. Moreover, the electronic cross-cabin coupling can convey the information necessary to the helicopter pilots to act timely in low-level flights. The next chapter moves on to discuss the ability to automatically decouple inceptors in case of takeover control.

6.5 Concluding Remarks

In short, the main conclusions of this chapter are:

- The SAGAT method allows the objective measure of SA, therefore the contribution of the inceptor coupling system to the pilot awareness can be quantified.
- Regarding the awareness of the trainee pilot inputs, the force feedback contributed positively to the FIs in task of monitoring the performance of the trainee pilot. Using the coupled inceptors, pilots correctly informed the input of the trainee pilots in 11 of the 12 queries, while this value was reduced to 3 out of 12 queries for the uncoupled inceptors. All pilots indicated that visual cues could not compensate the force feedback provided by the coupled inceptors. Also, pilots considered the electronic coupling of the active inceptors alike the true mechanical linkages across the cabin.
- Regarding the overall SA, the results indicate that the coupled inceptor configuration provides a positive impact on the SA of the FI. The number of correct answers of all three pilots to the SA questionnaire using the coupled configuration was consistently higher compared to the uncoupled counterpart. The correct answers for the coupled design were 13% to 26% higher than for the uncoupled alternative, and the average difference of 19% represents a statistically significant increase. In other words, when the inceptor coupling is not present, part of the pilots’ attention is directed to understand the relation between helicopter response and the control inputs. When the inceptor coupling is present, the faster comprehension of the control inputs allows pilots to dedicate his/her spare attentional capacity to mission-related duties, as the monitoring task.
- In terms of SA levels, the inceptor coupling showed higher influence on the ability to project future states of the helicopter (SA level 3). The extra information conveyed by the force feedback of the coupled inceptor provided the anticipatory responsiveness, which proved to be meaningful in the flight near obstacles.
- The ability of the coupled inceptors to provide awareness through the inceptor to the FI was attested statistically. The results indicate that the electronic cross-cabin coupling can convey the information necessary to the helicopter pilots to act timely in low-level flights.

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7 Force Threshold Assessment

The chapter presents the evaluations performed for the force threshold assessment, in which the inceptor coupling configuration 2 (coupled including automatic decoupling) is analyzed. The description of the configuration can be found in subsection 4.3.1.

7.1 Test aim

The aim of this evaluation is to examine the influence of the automatic decoupling function on the helicopter flight. To this end, the following topics are analyzed:

- Investigation of the force fading logic influence on the control activity and attitude oscillation post-automatic inceptor decoupling
- Investigation of the optimum force threshold range for the automatic decoupling
- Analysis of the impact of the automatic inceptor decoupling on the flying qualities

Regarding the first aim, the development of an adaptive fading logic to compensate the opposing forces during takeover control maneuvers is feasible due to the unique ability of the active sidesticks to measure in real time the forces applied on inceptors. This logic targets to reduce the transients in control deflection and helicopter attitudes caused by the sudden deactivation of one control station in the automatic decoupling, as described in subsection 4.3.2.

Regarding the second aim, an optimum force threshold range for the automatic decoupling shall be identified since high force threshold can lead to control difficulty and low force threshold can cause unintentional inceptor decoupling.

Regarding the third aim, the investigation seeks to find if the automatic decoupling system can threaten the controllability in case of poor HQ. To this end, two types of helicopter are tested in the evaluations. The baseline helicopter is modified to characterize a vehicle with degraded stability compared to the initial one. The significance of this approach is the possibility to analyze the system in conditions representative of handling qualities (HQ) level 3, which may be expected in emergency or in atmospheric disturbances.

7.2 Method – Flying Qualities Analysis

The investigations of the automatic inceptor decoupling characteristics are carried out by means of HQ analysis. As defined by Cooper and Harper [139], handling qualities (or flying qualities) are "those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role".

The significance of this analysis is the concept that HQ deficiencies increase the chance of pilot error, hence can lead to accidents and incidents. Actually, previous researchers indicated a strong correlation between handling qualities and accident rates [140], [141]. Therefore, identification of these deficiencies in the early stages of a system development becomes paramount.

7.2.1 Method Description

The development of the optimum force threshold range is conducted by the analysis of the flying qualities after the automatic inceptor decoupling. This type of analysis generally has two equally important facets - the objective and the subjective aspects, which are addressed in a complementary way. The handling qualities can be assessed objectively through analysis measurements, and subjectively through pilot opinion of the ability to fly MTEs within defined performance constraints [122, p. 77].

Table 7.1 outlines the assessment methods, which are subsequently described by the evaluation phase. The rating scales are summarized in the next subsection.

Phase I: Force Fading Logic Effectiveness

The first part of the assessment consists of verifying the influence of the force fading logic, namely Counter Force, on the control overshoot and attitude oscillation after the automatic inceptor decoupling. The objective measurement of these parameters is used to compare the attitude and control transients with and without the Counter Force logic.

Phase II: Development of the Optimum Force Threshold Range

The second phase involves subjective and objective data gathering for the analysis of the attitude and control transients after the automatic inceptor decoupling. To this end, takeover control maneuvers by the FIs are employed in different force thresholds. The assessing pilot awards ratings for the resulting transient effects of the decoupling using the transient rating (TR) scale [142]. The classification of the transient effects is plotted against the control deflection and helicopter attitude variations to define an envelope for the force threshold, whereby the optimum range can be identified.

Phase III: Validation of the Optimum Force Threshold Range

Whereas one test pilot participated in phase II to develop the optimum force threshold range, three test pilots are invited to validate the FT range in phase III. Moreover, the invited pilots assign ratings in two additional scales, the pilot handling qualities rating (HQR) [139] and the pilot induced oscillations rating (PIOR) [143]. These ratings are useful to outline any limitation on flight safety resulted from deficiencies in flying qualities due to the inceptor decoupling.

Table 7.1: Methods in the force threshold assessment

Method	Goal	Parameter	Rating Scale	Evaluation Phase
Objective data	Measurement of transients	Control activity and helicopter attitude variation	Not applicable	I, II, III
Subjective pilot rating	Classification of transients	Control activity and helicopter attitude variation	Transient rating (TR) [142]	II, III
	Classification of oscillations	Helicopter attitude oscillations	Pilot induced oscillations rating (PIOR) [143]	III
	Controllability analysis	Helicopter characteristics and pilot effort compensation	Handling qualities rating (HQR) [139]	III

7.2.2 Rating Scales

Transient Rating Scale

The TR scale was developed by Hindson *et al.* [144] in support of the development of an experimental fly-by-wire helicopter, and modified by Weakley *et al.* [142] in the V-22 study for flight control failures. The complete modified version is shown in Appendix D.2. The decision tree-based scheme is structured in two columns corresponding to transient response (short term effects) and recovery (mid-term effects). Each column can be rated from A to H. The present research focused on the transient effect only, as defined in Table 7.2, but the complete scale was available to aid pilots in the definition of the ratings. The actual scale starts the decision tree including the sentence 'failure occurs', due to the interest in transients after FCS degradation. The present research modified the sentence to 'task occurs', in order to adapt to the scope of the thesis.

Table 7.2: Transient rating scale [144]

Transient Effect	Rating
Minimal excursions in aircraft states	A
Minor excursions in aircraft states	B
Moderate excursions in aircraft states and controls but not objectionable	C
Objectionable excursions in aircraft states and controls; operational flight envelope[1] exceedance not a factor	D
Very objectionable excursions in aircraft states and controls; operational flight envelope[1] limits approached	E
Excursions in aircraft states may result in encounter with obstacles, unintentional landing or approach on safe flight envelope[2] limits	F-G
Catastrophic encounter with obstacles or structural failure	H

This methodology has been extended to produce an integrated classification, as described in Figure D.2 [145]. The integration combines the severity category concept (minor, major, hazardous, and catastrophic), the TR and the HQR, and was adopted in the certification of the NH90 helicopter [122, p. 573]. The minor safety severity elicits a rating A or B, which is equivalent to level 1 HQ. The helicopter falls into the level 2 category if the ratings are C or D. Major failures correspond to degradations to level 3 HQ. Hazardous or catastrophic corresponds to the level 4 region, where the controllability is threatened.

Pilot Handling Qualities Rating Scale

HQR can be defined as the explicit measurement of pilot workload and implicit measurement of aircraft stability and control characteristics [122, p. 511]. Figure 7.1 summarizes the HQR scale, and the complete scale can be found in Appendix D.4. Also-called Cooper Harper scale, the one is structured as a decision tree. The evaluation pilot answers to a series of dichotomous (two-way) choices which will lead him/her to the rating. The scale ranges from 1 to 10, with 1 indicating the ideal handling characteristics and 10 the uncontrollable case. The scale is divided into three levels, as shown in the last column of Figure 7.1. The last rating (HQR 10) is commonly referred to as level 4,

[1] Operational flight envelope (OFE): user-defined, required to fulfil the user's function.
[2] Safe flight envelope (SFE): manufacturer-defined, sets the limits to safe flight, represents the physical limits of structural, aerodynamic, power plant, transmission or flight control capabilities.

but it is not included in the original scale. A comprehensive discussion about the HQR scale is presented in [146].

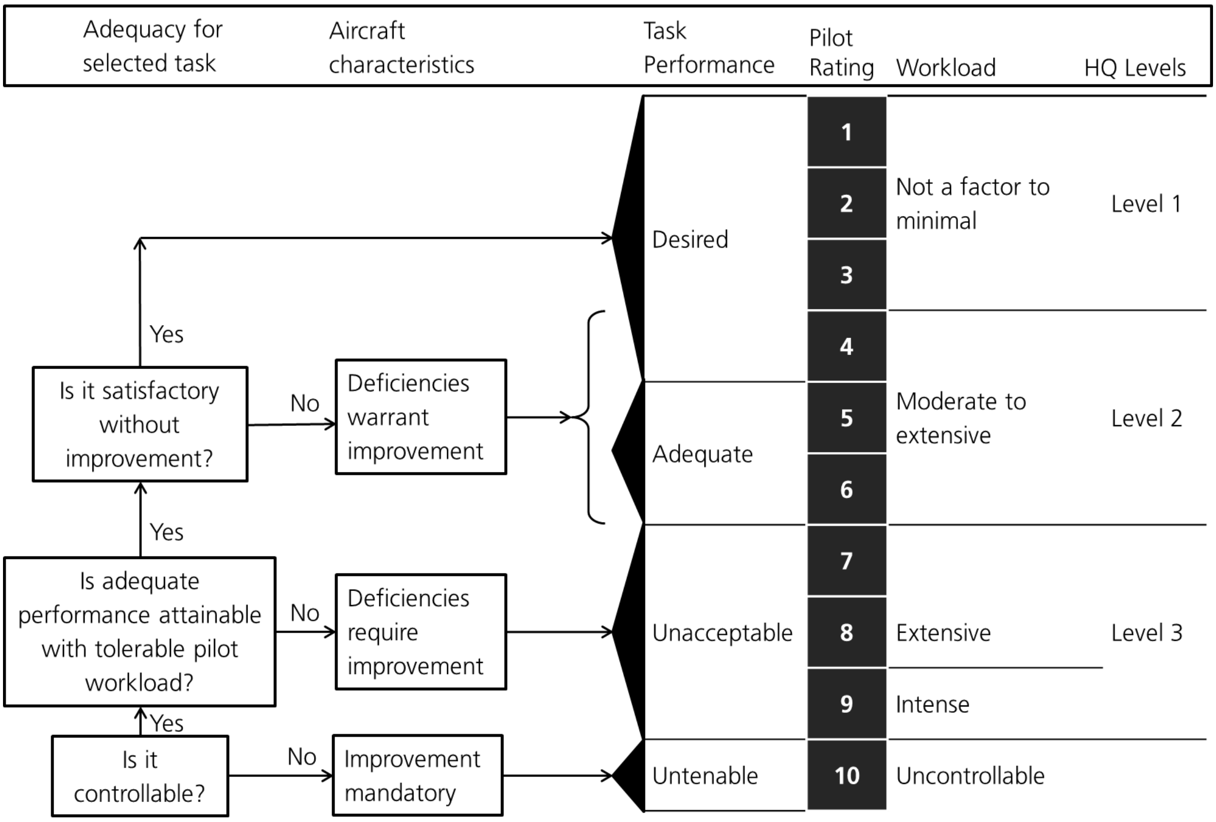


Figure 7.1: Handling qualities rating scale- summarized from [139]

Pilot Induced Oscillations Rating

Pilot induced oscillations are “sustained or uncontrollable oscillations resulting from efforts of the pilot to control the aircraft” [147]. This condition occurs when there is a coupling of the frequency of the pilot's inputs and the aircraft's own frequency. Thus, the pilot may tend to overcorrect the attitude error in opposite direction, which can lead to dangerous oscillations.

PIO rating scales have been introduced as a PIO tailored extension of more comprehensive HQR scales [148]. The scale used in the experiments (Figure D.4) standardizes the PIO gravity by classifying the severity of the possible oscillations. The ratings vary between 1 and 6, being 1 the condition without tendency to undesirable oscillations and 6 the worst case, when even smooth pilot inputs can trigger divergent oscillations.

7.3 Evaluations

7.3.1 Experimental Scenarios

Two experimental scenarios were developed to analyze the influence of the automatic decoupling on the takeover maneuvers in helicopter flight.

In the phase I, the task of approach to helipad MTE reproduces an inappropriate input of the trainee pilot close to ground, which leads the FIs to takeover control in low level flight. The task is illustrated in Figure 7.2, and fully described in Appendix B.3, which also includes the task performances in Table B.3. For comparison of the transients (control and attitude), the overriding action of the FIs is implemented at repeatable conditions. Hence, the height of the incorrect input was defined as 50 ft AGL. This part of the final approach to hover is called flare and is characterized by a nose up attitude to decelerate the helicopter and to slow down the descent rate. The inappropriate input of the trainee pilot is an excessive pitch up attitude, causing fast vehicle deceleration and a high rate of descent. The FI is required to takeover control via automatic decoupling, complete the approach and bring the helicopter to hover.

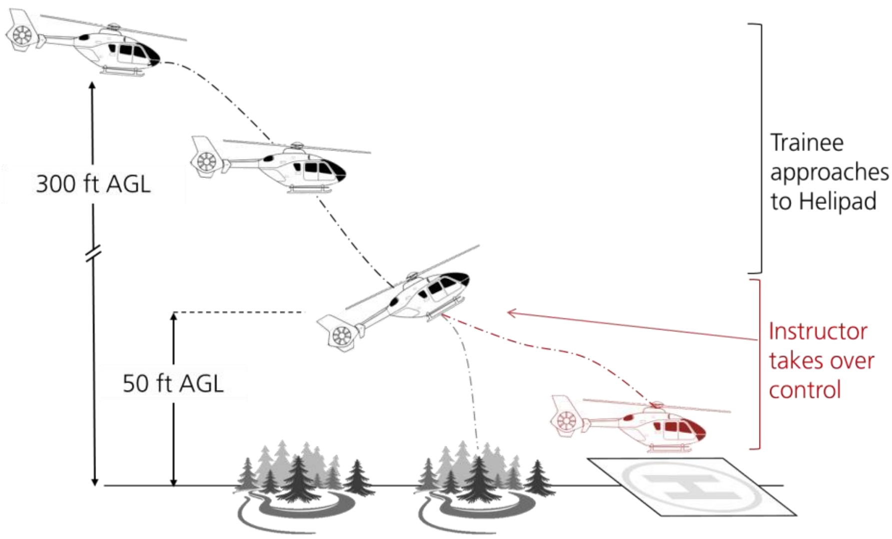


Figure 7.2: Approach to helipad MTE

In the phase II and III, the task transition to hover MTE is implemented. It consists in a deceleration to a repeatable, ground-referenced hover point from which rotorcraft deviations are measured. The task performance is identical to the hover MTE described in the ADS-33E [114], but the task conditions to achieve the proposed performances are distinct. While the experimental pilot performs the whole task in the original version, the adapted maneuver starts with the trainee pilot flying the vehicle, and the FI should takeover control when the recommended flight path is violated. When the automatic inceptor decoupling is activated, the FI shall complete the transition to hover. The task is depicted in Figure 7.3, its complete description is presented in Appendix B.2, and the task performances are shown in Table B.2. Figure 7.4 depicts the scenario, including the ground references used to maintain the task performance.

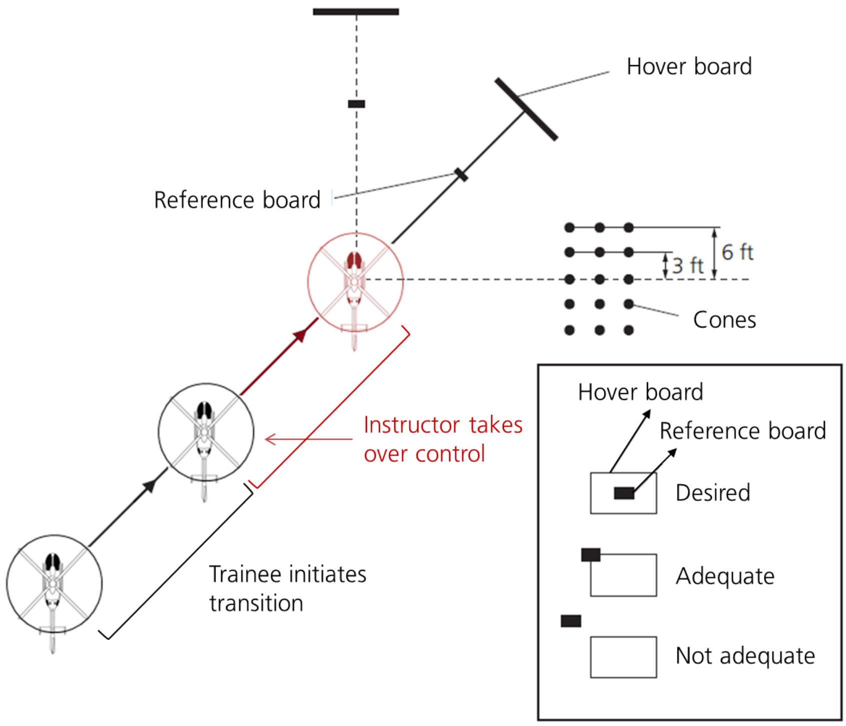


Figure 7.3: Transition to hover MTE

Figure 7.4: Ground references of the transition to hover MTE scenario

7.3.2 Procedures

Four test pilots participated in the force threshold assessment. Initially, pilot C flew as the FI in the phase I and II. After the development of the optimum force threshold range by the pilot C, three test pilots from the *Bundeswehr* Technical and Airworthiness

Center for Aircraft (WTD 61) were invited to validate the force threshold envelope previously developed.

The flight experience of the test pilots is described in Appendix C.2. All pilots are flight instructors and have test flight experience. Like the previous chapter, the experimental pilots are referred to throughout as the FI, since they acted as instructor pilots during the completion of the tasks.

The stability of the helicopter model is modified to obtain a comprehensive analysis of the force threshold's influence on handling qualities. The target is to reach a boundary which the inceptor decoupling could trigger control difficulties to pilots in high gain tasks. Two helicopter types were tested: the baseline helicopter (as described in the section 5.1.2) and a modified helicopter model. The latter differs from the former by adding time delay in the FCS and by modifying the values of the control response derivatives of the helicopter model. Those two procedures are explained in detail in the next subsection (7.3.3).

A briefing containing the scope of the research and system description was presented to the pilots, including the DLR test pilot who contributed as the trainee pilot. Each pilot flew at least three practiced trials before the recorded test point. The number of test points by assessment phase is indicated in the Table 7.3. The automatic inceptor decoupling was tested in equally spaced levels of FT between 20 N and 40 N.

Table 7.3: Test points for the force threshold assessment

Test aim	Phase	Pilots	No. test points	Helicopter model
Force fading logic effectiveness	I	C	200	Baseline
Optimum force threshold range (development)	II	C	90	Modified
Optimum force threshold range (validation)	III	D, E, F	42	Baseline, and modified

7.3.3 Helicopter Stability Modification

The modification of the helicopter stability allows the observation at performance limits to expose any potential handling cliff edges. In other words, the stability modification intends to ascertain if an inceptor decoupling in a degraded stability helicopter can lead to hazardous safety conditions, like events of loss of control.

The stability is an important concept to helicopter controllability, and, therefore, for the present investigation. The helicopter flight dynamics can be represented by linearizing the equations about a particular trim condition and by computing the eigenvalues of the aircraft system matrix [122, p. 28]. The stability of the helicopter can be determined by the stability of individual modes, which are indicated by sign of the real part of the eigenvalues (λ). A positive sign of the eigenvalue indicates instability and negative sign indicates stability. This type of representation of eigenvalues is called as root locus plot. The computed eigenvalues (λ) satisfy the equation [149]:

$$\det[\lambda I - A] = 0 \tag{7.1}$$

The modification of the helicopter stability was performed through changes in the control response derivatives. These variables influence the behavior of the helicopter in response to the pilot's control input [150]. The control derivatives θ and ϕ were reduced in 30% compared to the nominal values in the baseline helicopter, which affects the pitching and rolling response to cyclic longitudinal and lateral displacements, respectively. According to [150, p. 179], the control response is essential for determining the flying qualities of a helicopter, since the dynamic stability[3] is impacted by these derivatives [150, p. 179]. The influence of the modification is shown in Figure 7.5 through the root locus plot of the original helicopter model (baseline) and the degraded stability helicopter model (modified) in hover. The modified eigenvalues are less damped (upwards) and less stable (rightwards) compared to the baseline values. Both conditions are oscillatory, as the eigenvalues have an imaginary part.

Figure 7.5 highlights two helicopter dynamic modes. The phugoid mode is a longitudinal oscillatory motion. The phugoid pole, in the modified helicopter model, is marginally unstable, since it is placed in the right side of the complex plane, but close to the imaginary axis. The second dynamic mode is called Dutch roll, an oscillatory roll and yaw motion. The both baseline and modified poles related to the Dutch-roll condition are located in the stable side of the plot (left side of the abscissa axis).

The eigenvectors of the baseline and the modified model for phugoid and Dutch-roll modes are depicted in polar form for the hover condition, along with the helicopter response in translational velocities (u, v, w) and angular rates (p, q, r). Figure 7.6 shows the magnitude of the eigenvector components for phugoid oscillation. Since the mode is oscillatory, each component has magnitude and phase. The eigenvectors are normalized such that its magnitude equals unity. Translational velocity in x-axis significantly contributes to the phugoid oscillation in both modified and baseline helicopter models. Similarly, eigenvector components of Dutch-roll oscillation also have magnitude and phase as shown in Figure 7.7. Excluding the translational velocity in z-axis, all other

[3] The dynamic stability of an aircraft refers to how the aircraft behaves after it has been disturbed following steady non-oscillating flight [151].

parameters are observed to have significant influence on Dutch-roll mode. The translational velocity in x-axis is considerably more pronounced in the modified model.

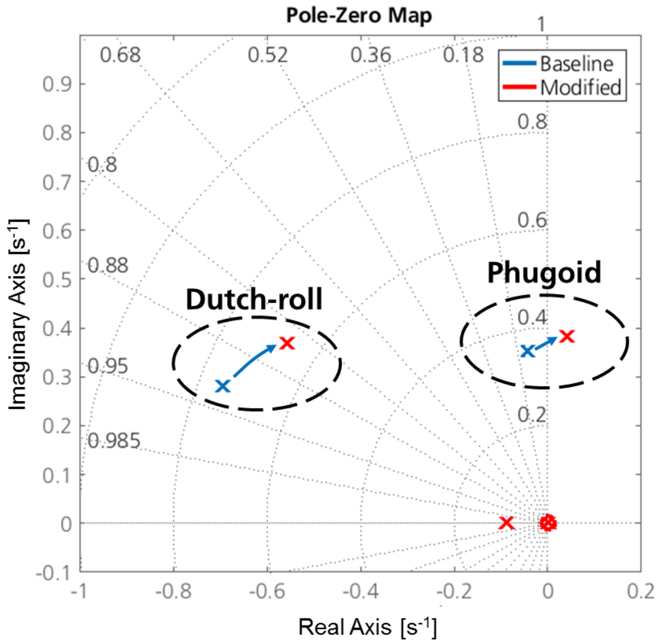
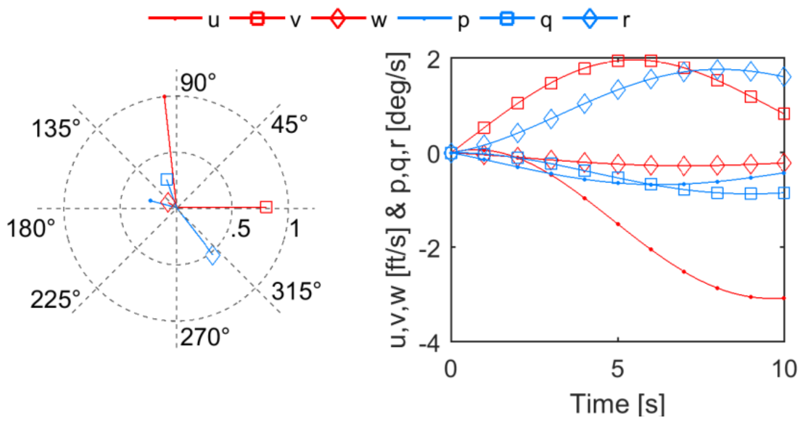
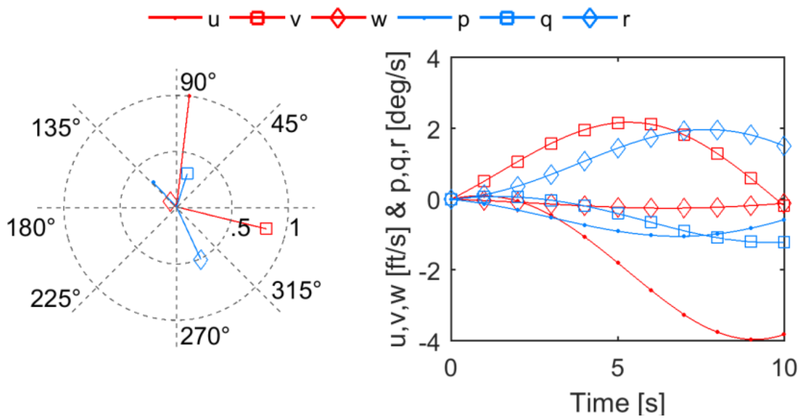


Figure 7.5: Root locus of the baseline and the modified helicopter model

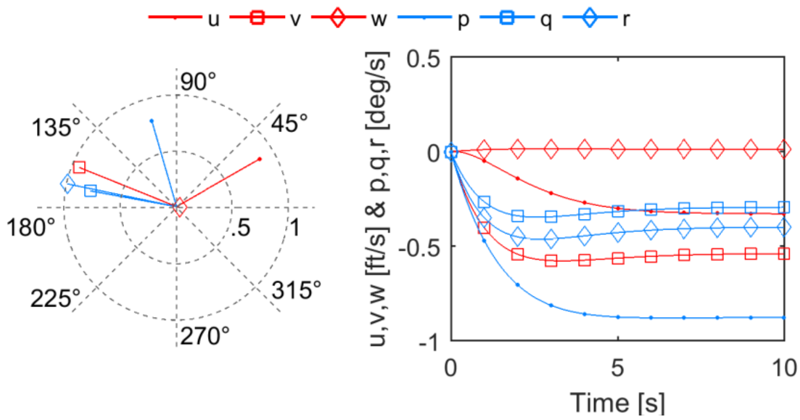


a) Phugoid oscillation, baseline helicopter model - eigenvalue (-0.041+0.353i)

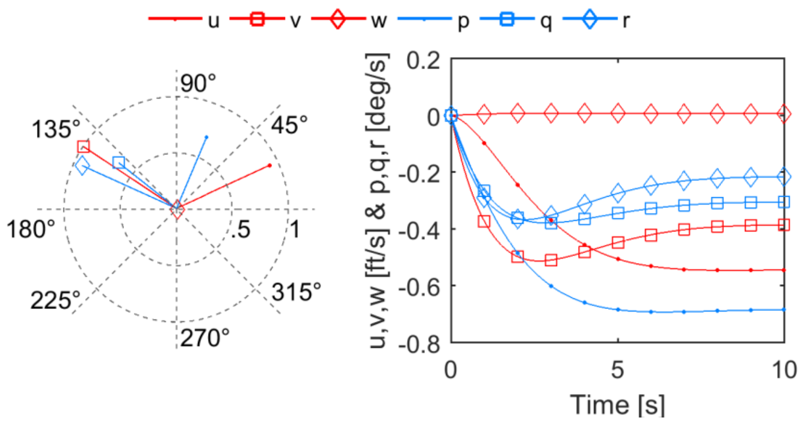


b) Phugoid oscillation, modified helicopter model - eigenvalue (0.042 + 0.383i)

Figure 7.6: Eigenvalues in hover (phugoid)



a) Dutch-roll oscillation, baseline helicopter model - eigenvalue (-0.696+0.280i)



b) Dutch-roll oscillation, baseline helicopter model - eigenvalue (-0.558+0.370i)

Figure 7.7: Eigenvalues in hover (Dutch-roll)

Time Delay

An additional form of stability modification is the introduction of a time delay with 300 ms in the FCS, which is likely to reveal poor handling qualities due to high gain tasks [152].

In rotorcraft, there exists a high inherent phase lag between inceptor input and vehicle body response due to the time required for actuator and rotor responses, besides digital computing, sensor signal shaping, and filtering. However, excessive time delay of the rotorcraft-pilot system can adversely affect the pilot controllability. Manual frequency sweeps were performed in both helicopter models to identify the influence of the extra time delay in the pilot-helicopter system. The bandwidth criterion is analyzed according to the criteria shown in Figure A.1.

Figure 7.8 shows the Bode plots of the frequency response data in pitch axis, and Table 7.4 presents the values of the frequencies and phase delay of the baseline and modified helicopter. It is important to note the steep slope of the phase delay in the modified helicopter plot. This condition results in large changes of phase lag for small increases in input frequency. Due to the drastic changes in the helicopter response, the pilot controllability and predictability are affected. The decrease in the bandwidth frequency of the modified helicopter (see Table 7.4) is likely to impact the flying qualities. The bandwidth frequency correlates to the highest frequency at which the pilot can make control inputs and still be able to correctly predict the aircraft response [153]. The probability of PIO increases in case of inputs at frequencies higher than the bandwidth frequency, because the helicopter motion is different in magnitude and phase.

Table 7.4: Bandwidth criterion results, pitch axis

Helicopter Model	Time Delay [ms]	ω_{180} [rad/s]	$\omega_{BW\,gain}$ [rad/s]	τ_d [ms]	$\omega_{BW\,phase}$ [rad/s]
Baseline	0	5.23	2.06	0.08	3.89
Modified	300	3.13	1.76	0.42	1.92

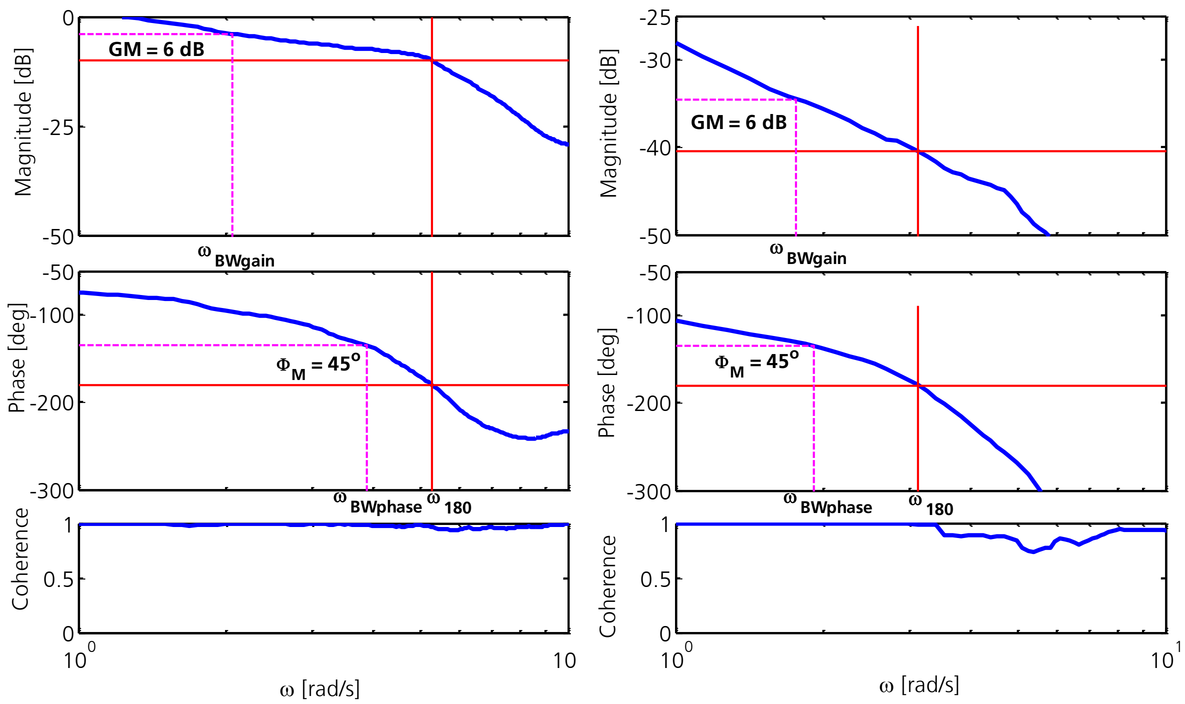


Figure 7.8: Bode plots of pitch axis in hover for baseline (left, time delay 0 ms) and modified (right, time delay 300 ms) helicopter model

Handling Qualities of the Modified Helicopter (Predicted Criteria)

The modified helicopter model was tested against the predicted criteria of the ADS-33E [114]. Figure 7.9 exemplifies the examination. For the three axes analyzed, the combination of the reduced bandwidth together with the increased delay in the modified helicopter (orange triangle) causes degradation in the handling qualities level. The complete evaluations for the predicted criteria are included in the Appendix A.3.

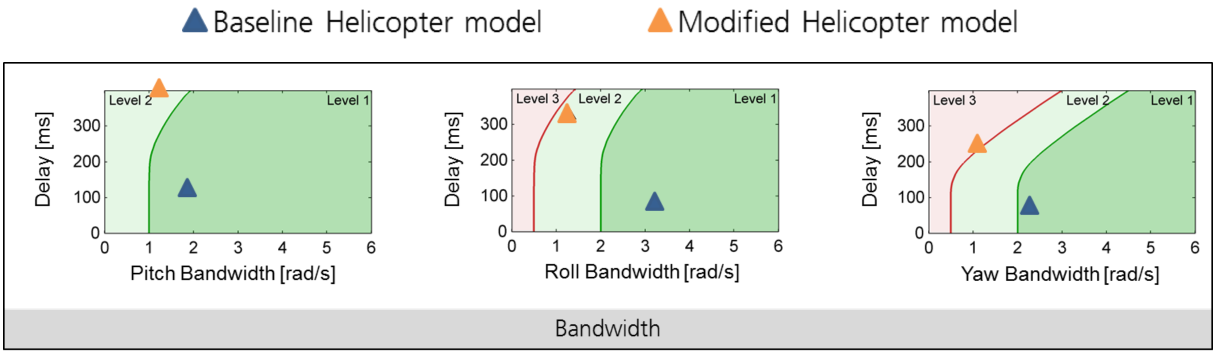


Figure 7.9: Bandwidth criteria of the baseline and modified helicopter

7.3.4 Statistical Analysis

ROC analysis

The receiver operating characteristics (ROC) graph is a technique for visualizing, organizing and selecting classifiers based on their performance [154]. ROC graphs are two-dimensional graphs that illustrate the diagnostic ability of a binary classifier system as its discrimination threshold is varied.

To exemplify the method, suppose a test pilot flying a maneuver including variation in pitch axis. After the maneuver, the pilot awards a rating to indicate if the test point is severe or non-severe from the safety perspective using a given criterion. Since the classification categories are likely to overlap (superimposed areas), the cutoff point is the value that better represent the threshold between these categories (Figure 7.10). Each observation in the data generates a binary response classification matrix in form of predicted probability (a continuous value between 0 and 1) of the severity result, based on pitch attitude variation. This leads to choose a cutoff point on the probability scale. For instance, if the predicted probability exceeds the chosen threshold in terms of pitch variation, the result tends to be positive (i.e., the severity is likely to be correctly detected) [155].

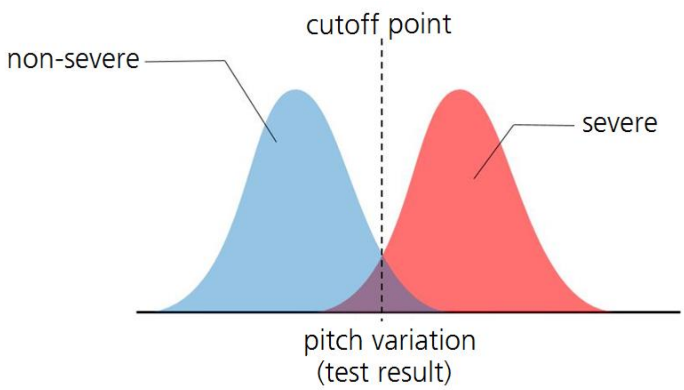


Figure 7.10: Example of cutoff point

Cutoff point dichotomizes the test values, so this provides the diagnosis (severe or non-severe in the example). The identification of the cutoff point value requires a simultaneous assessment of the proportion of subjects who are correctly diagnosed as severe (sensitivity or true positive rate) and the proportion of subjects who are correctly diagnosed as non-severe (specificity or true negative rate) [156]. The mathematical properties of the ROC curve can be found in [156, pp. 66–129].

The ROC curve is created by plotting the "1- specificity" against sensitivity at various threshold settings, as shown in Figure 7.11 [157]. Every point on the curve corresponds to a cutoff value. That is, the ROC curve visualizes a sweep through all the cutoff thresholds, so the performance of the classifier across all cutoff thresholds can be identified [158, p. 11], [157].

The chance diagonal is a line joining (0, 0) and (1, 1), which divides the curve into two equal parts (blue line in Figure 7.11). When ROC curve falls on this line, it indicates that results from diagnostics test are pure guess and there is random chance to distinguish subjects with versus without the investigated characteristic. The perfect predictor has a single point on the graph with 100% sensitivity and 100% specificity: the upper left corner of the unit square. At this point (1 - specificity =0, sensitivity = 1) a diagnostics test perfectly distinguishes between the severe and non-severe (the tails of the normal distributions do not overlap), which almost never happens in practice [158, p. 10].

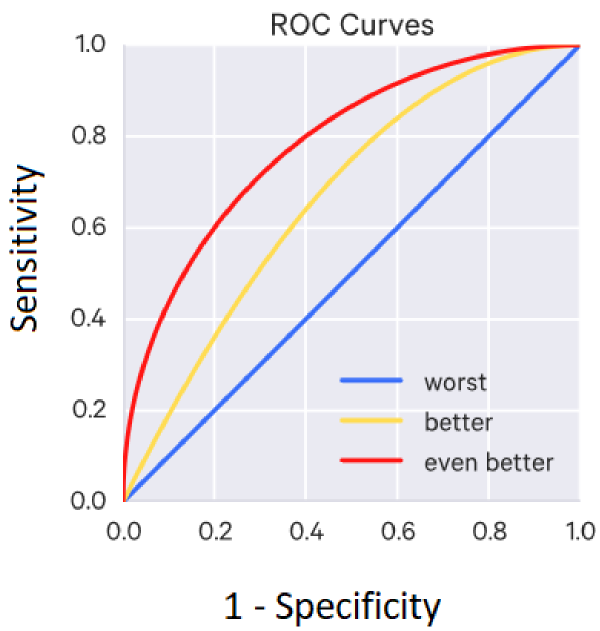


Figure 7.11: ROC graph [157]

The optimum cutoff point is defined as the point minimizing the Euclidean distance between the ROC curve and the plot point (0,1), and indicates the higher discriminating capabilities among the thresholds. The distance to the upper left corner of the ROC curve for each cutoff value is given by

$$d = \sqrt{(1 - sensitivity)^2 + (1 - specificity)^2} \tag{7.2}$$

In summary, the ROC curve provides the optimum cutoff point, i.e., the threshold that makes the resulting binary prediction as close to a perfect predictor as possible [159]. Moreover, the area under the ROC curve is used to quantify how good the classification algorithm is. Thus, a larger area represents a better predictor model. Typically, an area under the curve between 0.8 and 0.9 is interpreted as a very good model, and values above 0.9 are considered outstanding predictor to discriminate the investigated threshold [160, p. 162].

Boxplot

The boxplot is a standard technique for presenting the distribution of data based on the 5-number summary, which consists of the minimum and maximum range values, the upper and lower quartiles, and the median [161].

The box indicates the positions of the upper and lower quartiles. The interior of the box indicates the interquartile range, which is the area between the upper and lower quartiles and consists of 50% of the distribution. The box is intersected by a crossbar drawn at the median of the dataset [162]. By definition, the median provides the center point of the data, at which half the values are above the point and half are below.

The lines extending vertically from the boxes are known as the "whiskers", which are used to indicate the extreme values in the dataset. These are simply the minimum and maximum of a set of data, unless outliers are depicted. If an outlier is showed, the extremes of the whiskers are limited to 1.5 times the interquartile range (3rd quartile - 1st quartile) [163], and the outlier is a point greater than the mentioned boundary.

The median is said to be more robust against outliers than the classical measures of the normal distribution (mean value and standard deviation) [121]. Given the data $\mathrm{x} = (1, 1, 4, 4, 4, 4, 5, 6, 8, 8, 8, 12, 19, 19)$, the histogram and boxplot follow as depicted by Figure 7.12.

This collection of values is a quick way to summarize and compare the distribution of a dataset. Also known as 'box and whiskers diagram', it can easily illustrate the degree of dispersion and skewness of the data by the spacing between the different parts of the box.

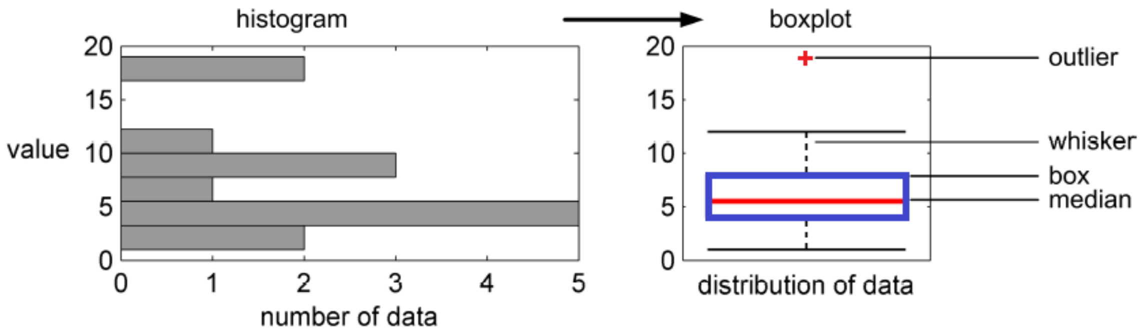


Figure 7.12: Boxplot structure [121]

7.4 Results and Discussion

7.4.1 Results

Preliminary Tests – Minimum Force Threshold

In preparation for the force threshold assessment, exploratory tests were performed to analyze the minimum force threshold for the inceptor decoupling. Through the transverse repositioning task used in the SA test, pilots A, B and C were oriented to interfere in control to adjust the trainee pilot inputs according to task performance, but without taking over control (just assisting the trainee pilot). The automatic decoupling (configuration 2) was activated. The goal was to identify the force threshold that enables the FI to assist the trainee pilot without unintentional inceptor decoupling. Starting in force threshold of 5 N, this level was modified in steps of 5 N. Pilots state that 5 N was simply impossible to apply any input without decoupling. The corrections on control were eventually possible for 10 N and 15 N, but the inceptor decoupling was inadvertently triggered at least two times per pilot. The first boundary to permit the assistance without unintentional force decoupling was 20 N. FIs repeated the test points for 20 N and tried to apply force until the inceptor decoupling was initiated. They stated that the force used to decouple inceptors at 20 N was representative of a full intervention (in other words, to takeover control completely and not to assist pilot by partial interference). Therefore, the value of 20 N was defined as the minimum to avoid unintentional decoupling.

Phase I: Force Fading Logic Effectiveness

The approach to helipad scenario (Appendix B.3) was used to investigate the performance of the FIs in takeover maneuvers using the automatic decoupling function. The time-critical task motivates the FIs to interfere on control in pitch axis. The independent variable is the force threshold (FT) to decoupling and the Counter Force logic. The dependent variables are the control deflection and the pitch attitude variation.

Figure 7.13 illustrates the scientific investigation for a FT of 30 N. In the time = 0, the inceptors are decoupled due to the pilots' force in opposite side (upper plot). In the left side, the Counter Force is not activated after the inceptor decoupling. A control overshoot can be identified in the second plot, which leads to variation of the helicopter attitude rate and attitude angle. In the right side of the figure, the opposing force reduces the control overshoot and contributes to decrease the resulting attitude variations. The orange arrow in the lower plot highlights the attitude behavior and indicates that the FI only corrected the excessive pitch up angle and brought the helicopter to hover, in case of assistance of the force fading logic. Without the Counter Force, the FI increased the helicopter speed inadvertently due to the excessive pitch down attitude, which triggered subsequent variations.

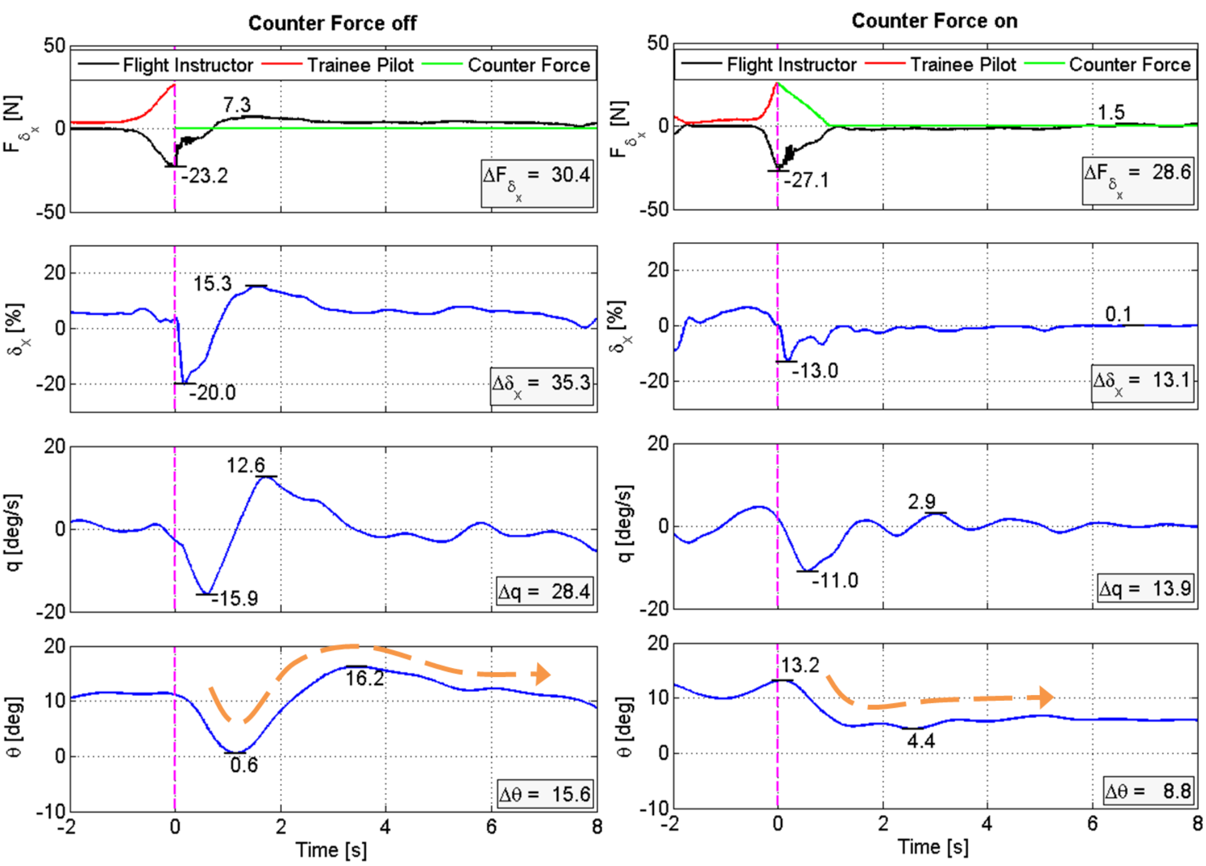


Figure 7.13: Influence of Counter Force in the takeover maneuver

In total, 200 test points are analyzed by the pilot C for the baseline helicopter. Five equally spaced levels of FT between 20 N and 40 N were assessed. For each FT, 20 test points examined takeover control maneuvers including the activation of the Counter Force, and another 20 test points were dedicated to analyze the maneuver without this logic. The complete dataset is presented in the Table E.4 (control deflection) and Table E.5 (pitch attitude).

Figure 7.14 depicts the result in boxplot graphs. The transients in control and attitude increase gradually with the FT. However, the increasing gradient of the green boxplots (Counter Force off) is higher than the blue ones (Counter Force off). It reflects the adaptive characteristic of the force fading logic, which is adjusted according to the force at the moment of the decoupling. The differences in the transients of the two analyzed parameters are described in the Table 7.5 and Table 7.6. After the introduction of the force fading logic, the median values of the control deflection reduced between 62% and 59%; and the median values of the pitch attitude decreased between 39% and 50%.

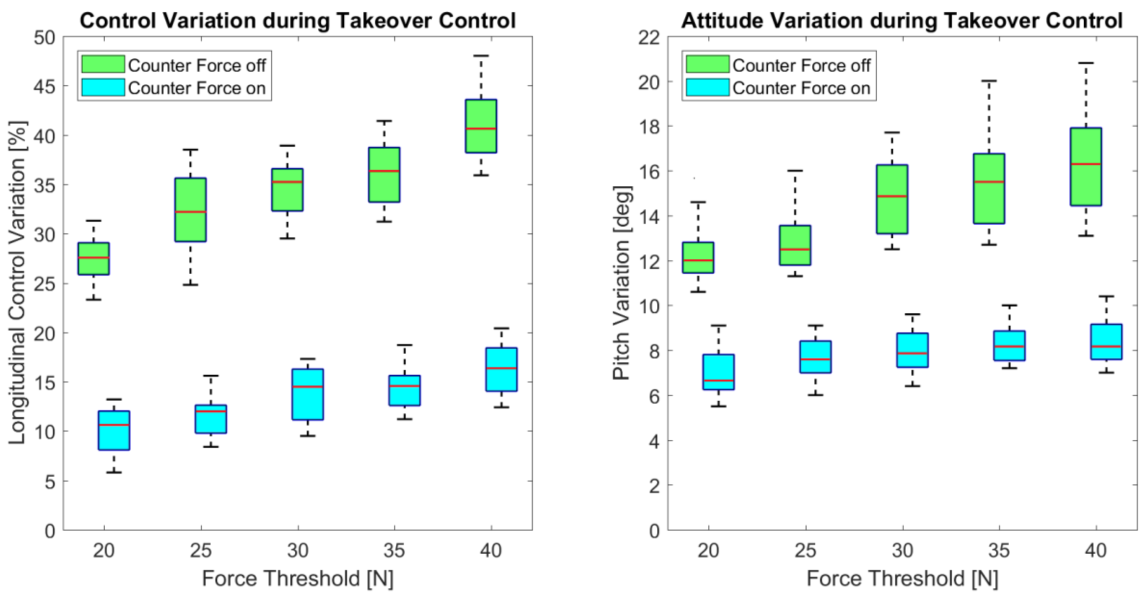


Figure 7.14: Boxplots of control and attitude variation for the baseline helicopter

Table 7.5: Median and difference values for control deflection variation

Force threshold [N]	Median control deflection [deg]		Difference [deg]	Difference [%]
	Counter force on	Counter force off		
20	10.6	27.6	17.0	62
25	11.9	32.2	20.3	63
30	14.4	35.2	20.8	59
35	14.5	36.3	21.8	60
40	16.3	40.6	24.3	60

Table 7.6: Median and difference values for pitch attitude variation

Force threshold [N]	Median pitch attitude [deg]		Difference [deg]	Difference [%]
	Counter force on	Counter force off		
20	6.6	12.0	5.4	45
25	7.6	12.5	4.9	39
30	7.9	14.8	6.9	47
35	8.2	15.5	7.3	47
40	8.1	16.3	8.2	50

Phase II: Development of the Optimum Force Threshold Range

The optimum force threshold range was developed using the task of transition to hover (Appendix B.2). The goal is to determine force threshold limits based on the effects of the transients after the inceptor decoupling that still can be classified as minor safety severity.

The helicopter model was the modified one, whose stability was changed to reproduce degraded flight qualities compared to the baseline helicopter. The control activity was computed as root mean squared (RMS), and not as peak variation, to account for both the mean and the variance of the control deflections. This approach is important considering a potential oscillatory behavior of the modified helicopter. The longitudinal axis was chosen because it represents the worst-case condition in terms of dynamic stability compared to the lateral axis.

Six different conditions were evaluated, among which there are three force levels (20 N, 30 N, and 40 N), and two force fading logic status (Counter Force on and Counter Force off). Fifteen test points were investigated in each condition. In total, 90 test points were evaluated. These points are described in Appendix E.2, and are divided by RMS control deflection (Table E.6 and Figure E.1) and pitch attitude variation (Table E.7 and Figure E.2).

The FI instructor awarded ratings for the resulting transient effects of the inceptor decoupling using the TR scale, as defined in Appendix D.2. The list of all ratings is included in the Table E.9. Two main criteria are applied for the ratings: a) uniform and predictable change in the helicopter states; and b) minimum control excursions and helicopter attitude transitions. The results, shown in Figure 7.15, are denoted by colors in the scatter graph. In general, the pilot rating progressively degrades with distance from the origin, which reflects an intuitively appropriate effect.

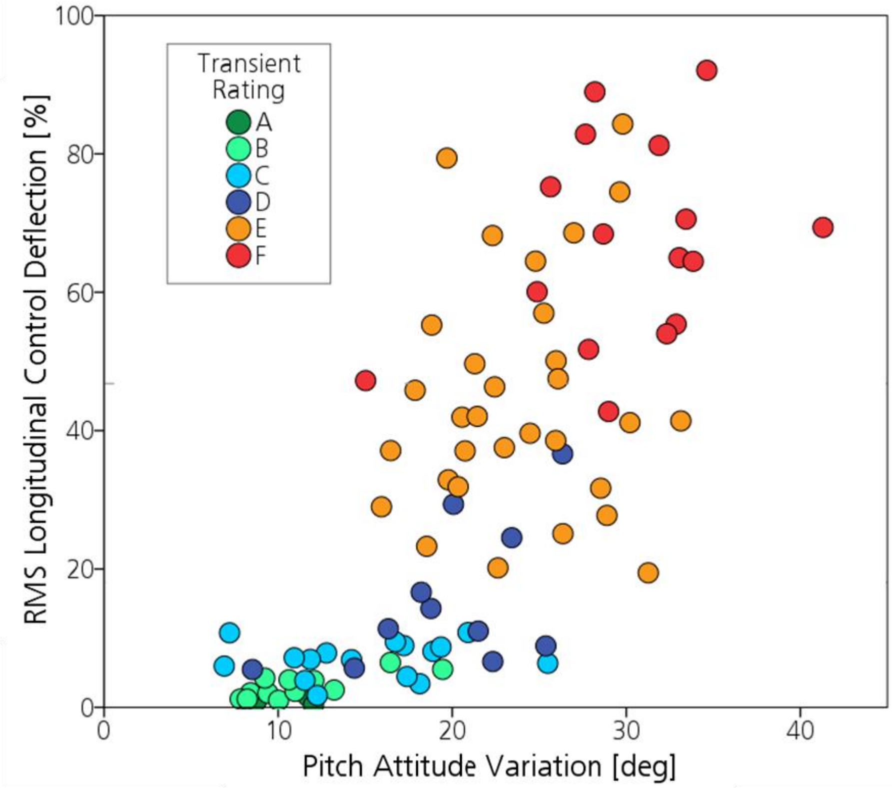


Figure 7.15: Transient rating for the transition to hover task

ROC graphs are calculated to identify the optimum cutoff point that represents the limits of the transient ratings according to the definitions of the integrated transient classification (Appendix D.3). In this scheme, the ratings A to D are associated to the minor safety severity; the rating E is linked to the major severity category; and ratings F and G are related to the hazardous severity category.

A normality test confirmed the normal distribution of the data in each condition of force threshold and Counter Force status (Appendix E.2, Table E.8). The ROC graphs are presented in Figure 7.16. The optimum cutoff points are the points minimizing the Euclidean distance between the ROC curve and the upper left corner of the graphs, which are indicated in the Table 7.7. Generally, models including area under the curve of 0.8 are considered very good classifiers. The areas under the curves in Figure 7.16 are higher than or equal to 0.9, which is an indicator that this model can discriminate the investigated threshold at very high precision [160, p. 162].

The values in the last column of the Table 7.7 are then inserted in the graph of the pitch attitude versus RMS control, which is shown in Figure 7.17.

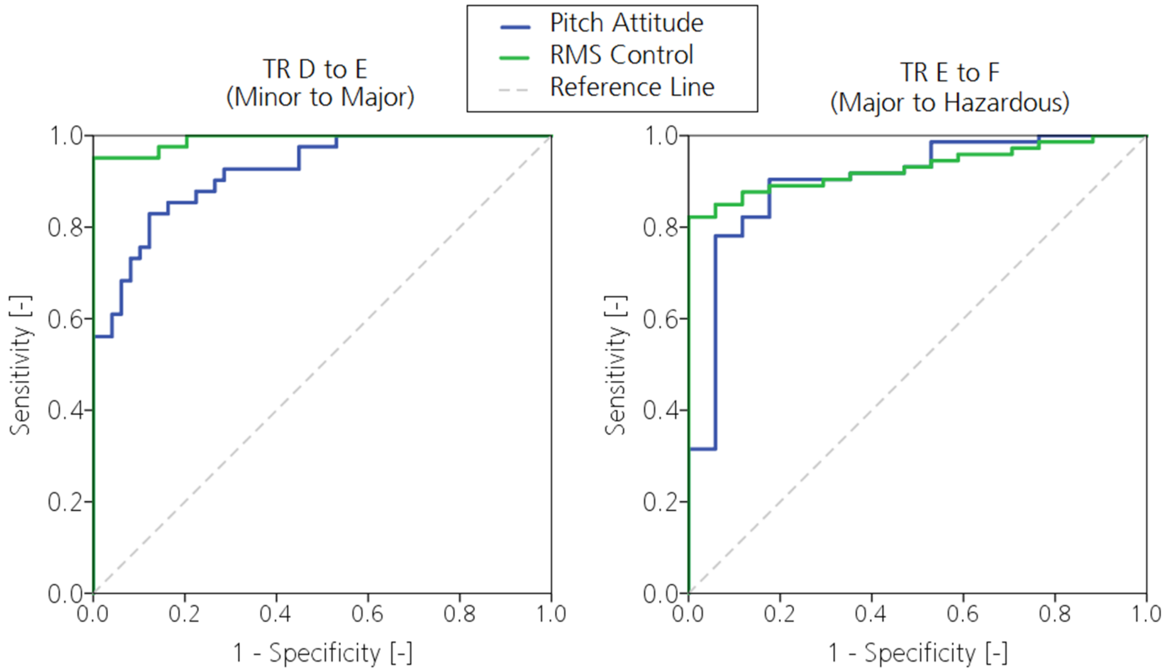


Figure 7.16: ROC graphs for RMS longitudinal control deflection and pitch attitude

Table 7.7: ROC graph values

Limit	#	Sensitivity	1-Specificity	Area under the curve	Value
Transient Rating D to E	RMS δ_x	0.95	0.00	0.99	18.05%
	Attitude θ	0.83	0.12	0.92	19.57°
Transient Rating E to F	RMS δ_x	0.85	0.06	0.93	46.80%
	Attitude θ	0.91	0.18	0.90	27.32°

The minor area starts at the origin of the graph and extends transversely to the point of intersection of the optimum cutoff points regarding the transient rating D to E. Due to the rectangular shape of the thresholds, it can be concluded that the FI was tolerable to variations in attitude (abscissa axis) until 19.6°, but only in case of low control activity, as indicated in the ordinate axis. Similarly, the major area is defined by the intersection of the optimum cutoff point regarding the boundary of the transients E to F. Since no points were assigned for the transients G and H, the boundary of the hazardous and catastrophic cannot be drawn.

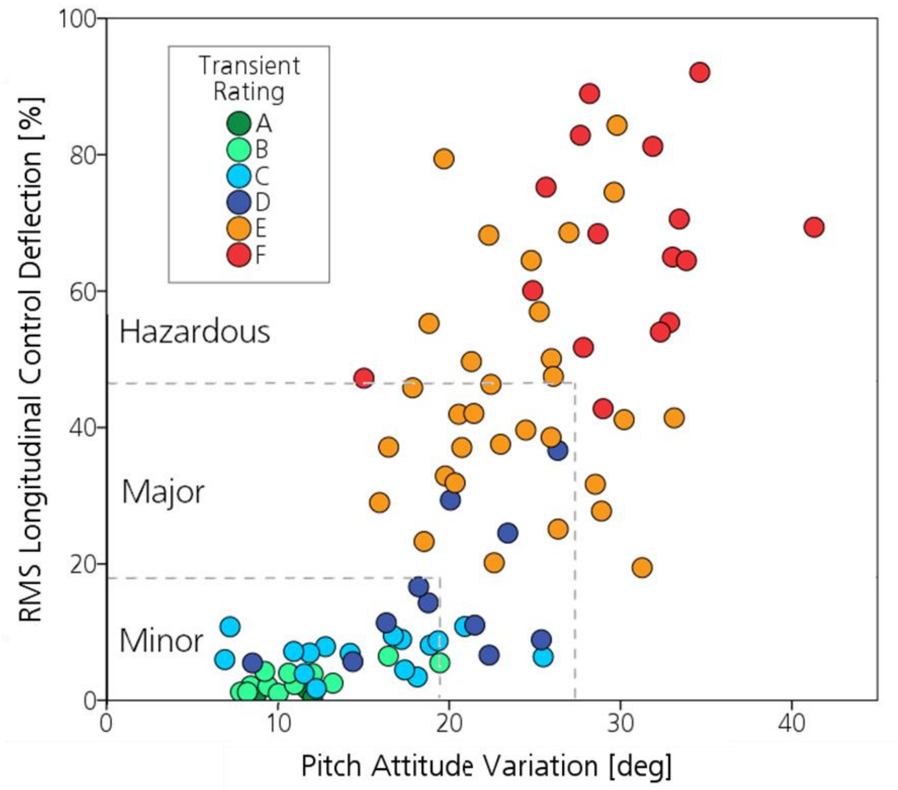


Figure 7.17: Pitch attitude versus RMS control (development of optimum FT range)

Phase III: Validation of the Optimum Force Threshold Range

The validation of the optimum force threshold range was performed by three test pilots in the task of transition to hover (Appendix B.2). The goal is to assign TR and compare with the force threshold envelope previously developed. Additionally, the FIs flew the transition to hover task (including inceptor decoupling) and the hover task described in the ADS-33E (without control transfer). The target is to compare the PIOR and HQR for two conditions, in order to verify the impact of the inceptor decoupling in the flying qualities.

The Counter Force was tested in two conditions (on and off) for three FT levels (20 N, 30 N, and 40 N). Also, the FT of 220 N was examined, which is representative of the configuration 1 (permanently coupled inceptors) and corresponds to the emulation of the cross-cabin mechanical linkages. These seven settings were tested in both helicopter models (baseline and modified). A total of 42 test points were recorded.

Figure 7.18 presents the ratings assigned by the FIs regarding the transients after the automatic inceptor decoupling in takeover maneuvers. The values of all test points are described in Table E.10 and Table E.11. On the left side of the Figure 7.18, the points for the Counter Force off condition are distributed along the graph in nearly linear fashion. These points can be found in all three severity areas. On the right side of the same figure are situated the test points when the Counter Force was activated. The points are rather grouped in the lower part of the graph, showing that the control activity decreased in comparison with the Counter Force off case. Also, only points in minor and major areas are found.

Based on the Figure 7.18, three major conclusions can be pointed out. Firstly, the envelope previously developed is considered valid, because only in one case there was a higher TR than the one expected by the severity area limits. The rating in this case is located close to the border of the minor area. This is the rightmost point in the lower graph (40 N, modified helicopter, Counter Force on, TR E). Other cases of lower ratings than the ones predicted by the severity limits are not a problem in terms of safety and are considered accepted. Overall, there was a good agreement between the ratings and the envelope limits. It should be noted, however, that a larger number of points can increase the precision of the severity boundaries location.

The second key conclusion concerns to the effectiveness of the Counter Force in the modified helicopter. The control activity and attitude variation were alleviated even for the degraded stability cases. The majority of the test points for the cases of 20 N and 30 N were classified as TR A to C when the force fading logic was activated.

The third major conclusion involves the upper FT limit of the automatic decoupling. Table 7.8 indicates the maximum and minimum rating for each FT. Among the tested FT, only 40 N cases were assigned as TR E. The graph in the upper right side provides another indication that the FT of 40 N may be excessive for the takeover maneuvers. Even when the Counter Force was activated, the test points of FT 40 N (orange) are spreading outside the minor area, while the test points of FT 20 N and 30 N are all concentrated in the lower middle part of this severity category.

Indeed, the FT of 40 N highlights the significance of the present investigation. It represents a condition which an inceptor decoupling could induce transients that affect flight safety; thereby the benefits of the automatic approach could be largely affected. To provide a comprehensive analysis of the decoupling effects, the baseline and modified helicopter cases were combined to compare the inceptor decoupling settings (20 N, 30 N, and 40 N) to the condition that simulates the permanently coupled inceptors (220 N). The FT of 220 N is high enough that pilots do not reach this limit under normal flight conditions, so both pilots can apply force without triggering the inceptor decoupling. In this case, when the FI intervened on controls, the trainee pilot stayed on the loop for 1.5 seconds before relinquishing the inceptors. The rationale for this method is explained in subsection 4.3.1.

Figure 7.19 shows that the median attitude variation was higher for the case of FT 40 N than for FT 220 N, even with Counter Force on. This example points out to the need of set FT limits; otherwise the controllability may be threatened.

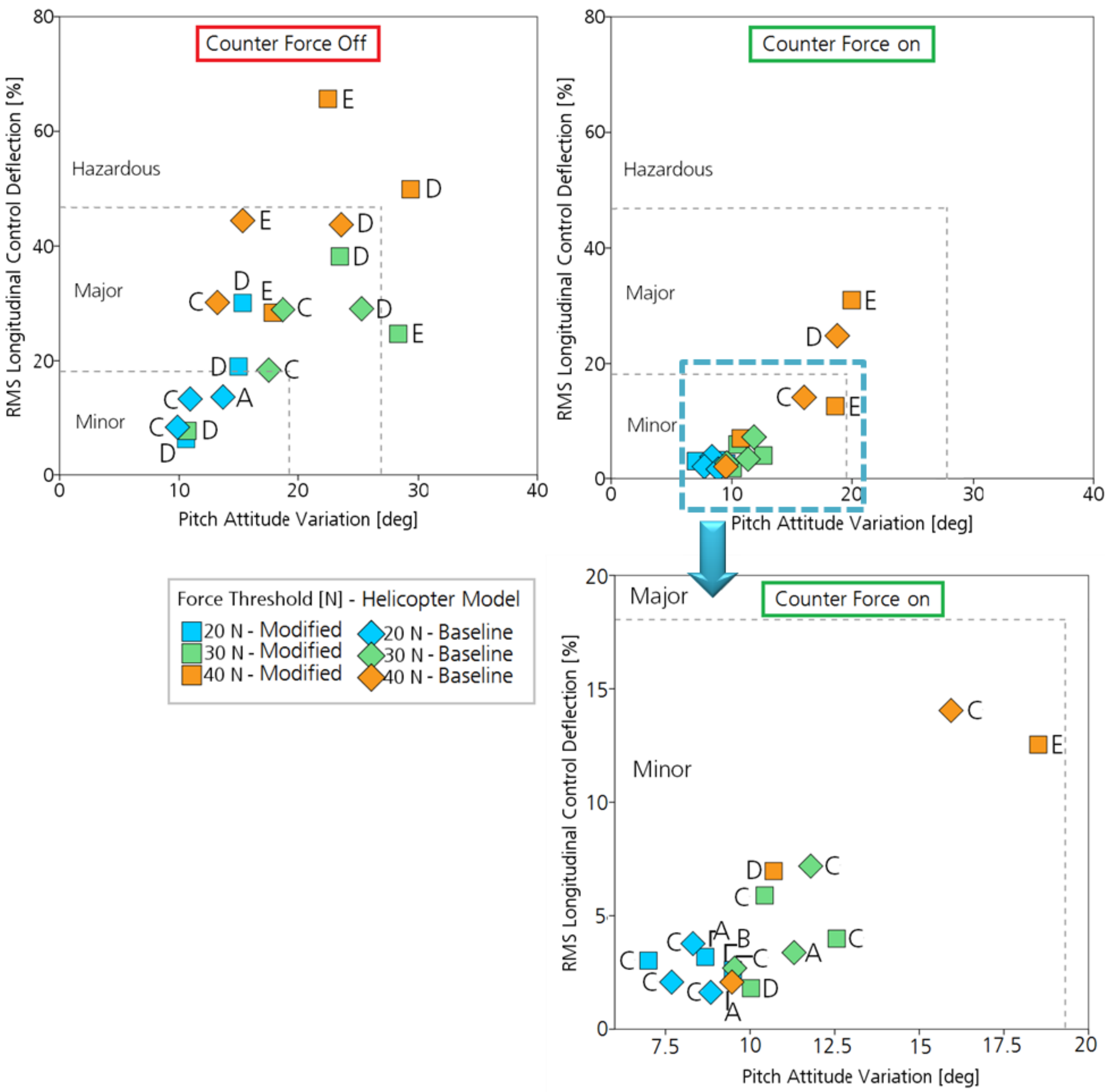


Figure 7.18: Pitch attitude versus RMS control (validation of optimum FT range)

Table 7.8: Minimum and maximum transient ratings

Helicopter	Force Threshold	Counter Force on		Counter Force off	
		Minimum rating	Maximum Rating	Minimum rating	Maximum Rating
Baseline	20 N	C	C	A	C
	30 N	A	C	C	D
	40 N	A	D	C	E
Modified	20 N	A	C	D	D
	30 N	C	D	D	E
	40 N	D	E	D	E

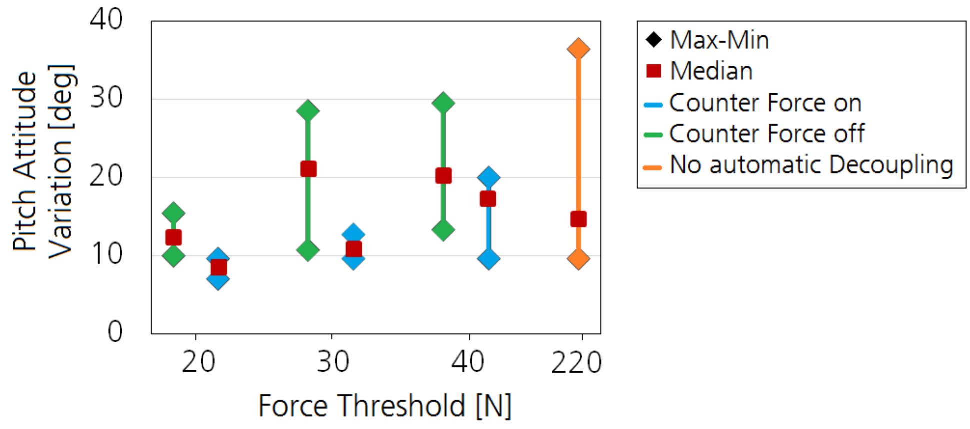


Figure 7.19: Maximum, minimum and median attitude transients by force threshold

Phase III: PIOR and HQR

Besides the TR, FIs assigned PIOR for the following 10 seconds after the inceptor decoupling. It should be noted that both baseline and modified helicopters are PIO prone, according to the handling qualities predicted criteria, which can be found in Appendix A. Moreover, the inceptor decoupling is a potential trigger for PIO. These events can be initiated by aggressive pilot control to avoid a sudden collision, pilot stress due to sudden changing of flight condition, and inaccurate piloting strategy [152].

Figure 7.20 shows two test points of the pilot E in the modified helicopter. Without the Counter Force, on the right side, the inceptor decoupling causes an overshoot in control deflection ($\delta_x = 21\%$ in the second subplot). The resulting neutral oscillatory behavior of the helicopter continues during the 30 s showed, influenced by the 300 ms time delay added in the modified helicopter. The FI assigned PIOR 4, which corresponds to reduction of the pilot gain to keep the control, but without inducing divergent helicopter motion. When the Counter Force is activated, on the left side of the figure, the introduction of the opposing force during the inceptor decoupling provides a positive effect in the helicopter behavior. The control variation is reduced as a consequence of the control stabilization due to the force fading logic. The effect lasted only during a certain period of time (around 20 s in this example), when the neutral oscillatory motion is again visible. The PIOR 3 was assigned, i.e., the helicopter motions can be prevented, but through considerable pilot effort.

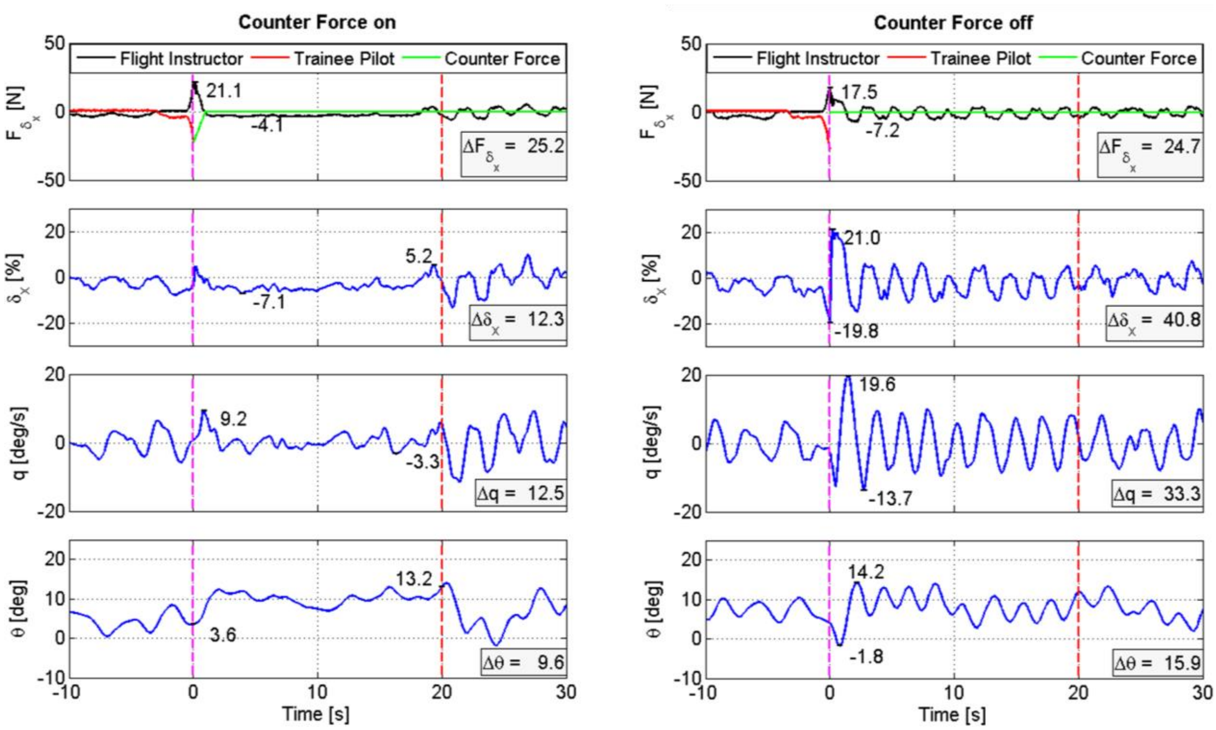


Figure 7.20: Influence of the Counter Force on the helicopter oscillatory behavior

The influence of the Counter Force on the PIOR is readily apparent in Figure 7.21. The pilot ratings are displayed for the four FT conditions (20 N, 30 N, 40 N, and 220 N), together with a dashed reference line. The dashed lines indicate the rating assigned by each pilot in the hover MTE as described by ADS-33E [114], i.e., the FI flies the task without interference or takeover control maneuver. It is used as a reference to compare the PIOR in the cases with and without control transfer. If the PIOR is lower for the automatic inceptor decoupling conditions, then it is likely that this function is not degrading the flying qualities, as indicated by the contrast of the blue and green bars against the dashed lines.

The blue bars indicate the PIOR for Counter Force on, and the green bars denote the PIOR for the Counter Force off. These two conditions were assigned 18 times in total. In the comparisons between the Counter Force conditions, 11 cases showed improvements of the force fading logic in terms of PIOR (lower rating), while 7 cases were rated equally. Moreover, the FIs judged that the PIO occurrence was generally alleviated by the inceptor decoupling using the Counter Force function (blue bars) compared to the reference case (dashed lines), since lower ratings were assigned in 15 out 18 cases.

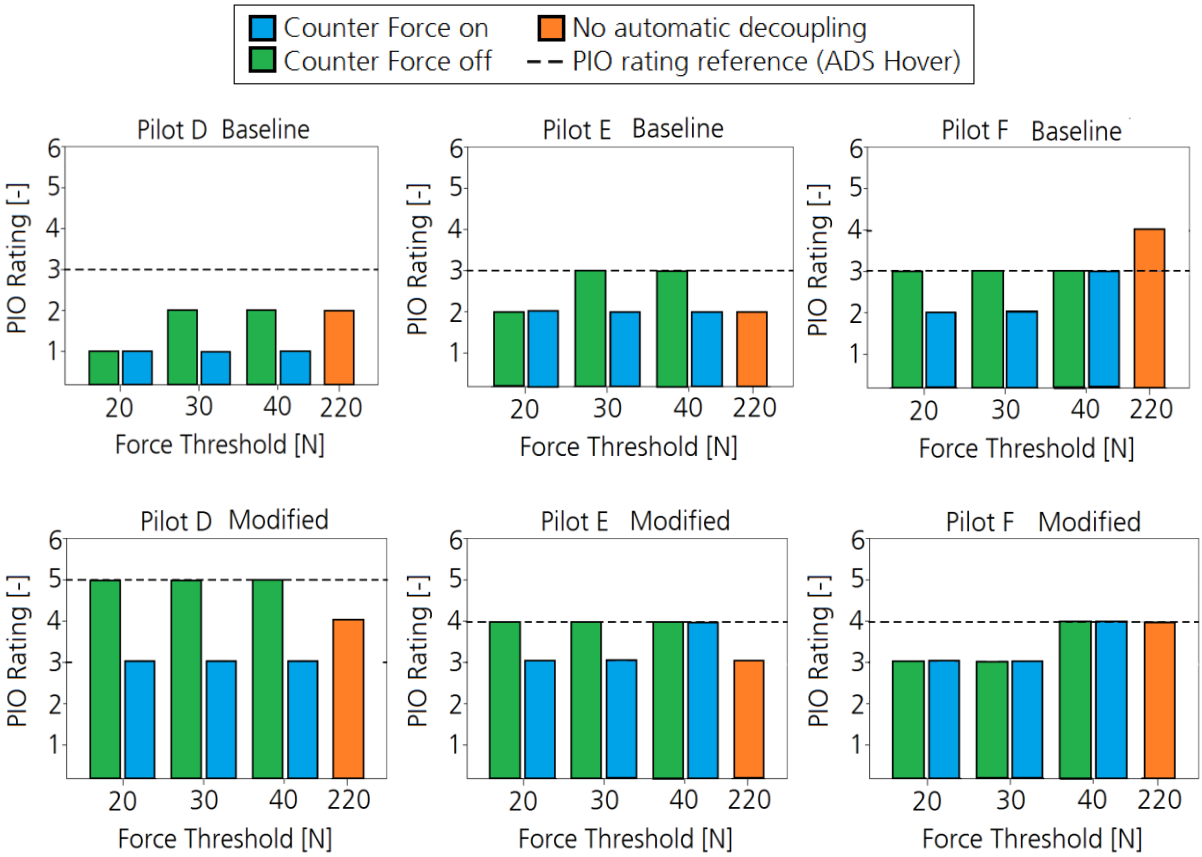


Figure 7.21: PIO ratings

Regarding the HQR, pilots awarded the baseline helicopter as HQ level 2, and the modified helicopter as HQ level 3. All the ratings are described in Table E.12. Only one FI (pilot D, modified helicopter) assigned a higher HQR for the takeover control task in comparison with the ADS-33E hover MTE. Even in this case, the variation did not change the HQ level (HQR 8 and 7, both HQ level 3). It means that there was no degradation of the HQ levels assigned. Therefore, it could be stated that the inceptor decoupling is usually not reducing the flying qualities in the transition to hover task.

In general, pilots reported that the inceptor decoupling without Counter Force produced a considerable 'control free play', i.e., inadvertent control overshoot, which is also referred to as overcontrol. In many cases, the FIs expressed concern about the proximity to the inceptor displacement limits, since less than 10% of control margin is generally considered insufficient.

The inceptor decoupling including the Counter Force activated was judged as intuitive and effective in most conditions, except for the FT 40 N, which was referred to as objectionable in some test points.

7.4.2 Discussion

The first part of the force threshold assessment was dedicated to investigate the influence of the force fading logic. In comparative trials, there is an effective reduction in the transients after the automatic decoupling when the logic is activated. There is a substantial transient decreasing in the condition of Counter Force on compared to Counter Force off for both parameters in terms of median values: reduction between 62% and 59% in control deflection; and between 39% and 50% in pitch attitude.

The context from which the results were extracted should be highlighted. It is noteworthy that a pitch axis correction was required, which implies that some transient was necessary to meet the objective of the task and to avoid ground collision. According to the task description, detailed in Appendix B.3, the trainee pilot applies an input up to 12 degrees and maintains that attitude about 50 ft above the ground. Considering that the pitch attitude for hovering in the proposed conditions is 5.8°, at least 6.2° are needed to correct the trainee input and bring the helicopter to hover.

Observing Table 7.6, there is an attitude variation of 6.6° to 8.1° in the pitch median values when the Counter Force was activated. In summary, there is a small addition of around 1° to 2° for the expected minimum variation. In contrast, when logic is deactivated, the additional median attitude varies by 6° to 10°. This difference can be meaningful for low level flights including obstacles around the helicopter. Additionally, it should be considered that the logic was effective to increase the piloting precision, since there was a lower control activity in the Counter Force on cases.

In the second part of the evaluation, the optimum force threshold range was developed. The minor severity category defined the limits of the optimum area, according to the statistical analysis. The research focused on defining the maximum tolerable condition in the sense that HQ remain within level 2 range, which corresponds to the minor category. Typically, flying qualities beyond level 2 shall be associated to emergency conditions, as severely degraded atmospheric conditions or following the loss of critical flight systems [122, p. 60]. One of the main applications of the automatic inceptor decoupling is to assist pilots in order to avoid accidents in time-critical conditions, therefore degradation in the flying qualities further than level 2 is highly undesirable.

It is worth mentioning the conservative aspect of the results. The transients after the automatic decoupling were analyzed in a modified helicopter including time delay with 300 ms and degraded dynamic stability. Even in these conditions, a good portion of the test points were found to be part of the minor severity area. It is not expected an aggravation of the analyzed transients (control activity and attitude variation) if the helicopter provides an equivalent or superior level of flying qualities in comparison with the tested helicopter model.

In the third part of the force threshold assessment, the optimum FT envelope was validated by three test pilots. There was a good agreement between the expected TR and the actual ratings assigned by the FIs. The Counter Force logic confirmed the effectiveness to reduce the control activity and attitude variation. The optimum FT range is specified between 20 N and 30 N. The lower boundary refers to the limit to avoid unintentional inceptor decoupling, while the upper boundary relates to the maximum FT which control oscillations are linked at least to level 2 handling qualities (minor severity area).

It should be highlighted that the investigation focused on the pitch axis because it was found to be more critical than the roll axis in terms of stability. However, these values cannot be direct transferred to the lateral axis. Due to the different capabilities of the human arm and wrist, the maximum force[4] in pitch axis is commonly indicated as 1.5 times the maximum force in roll axis. Hence, the roll FT limits for the present thesis was defined as 13.3 N and 20 N.

PIORs indicate that the inceptor decoupling is not acting as a trigger to degrade the PIO effects. Moreover, the Counter Force can stabilize the control deflections in case of oscillatory movements of the inceptors. It produces a transitory alleviation of the helicopter attitude that assists pilots in the controllability. Since the beneficial effect dissipates over time, there is no influence in the continuation of the flight, which is evident in the HQR assigned by pilots. The same HQ levels were generally assigned in the hover task including takeover control and the traditional hover task (ADS-33E). Since the task performances are the same in both tasks, it is notable that interference in control could be compensated by FIs, who accomplished the task after takeover control maneuvers.

7.5 Concluding Remarks

The main conclusions indicated throughout of this chapter are:

- The effects of the automatic decoupling via FT logics are analyzed in the baseline helicopter (ACT/FHS-like) and the modified helicopter. The latter consists in a degraded stability vehicle, in order to analyze if the automatic decoupling system can threaten the controllability in case of poor HQ.

[4] Maximum force measured in the extreme displacement point of the control envelope.

- Exploratory tests indicated the FT of 20 N as the minimum to allow the assistance by FI to the trainee pilot inceptors without unintentional force decoupling.
- The force fading logic (Counter Force) is implemented to mitigate control overshoots during the automatic inceptor decoupling. With FT between 20 N and 40 N, this logic alleviated the longitudinal control deflections by 62% to 59% during the takeover control tasks (approach to helipad scenario). Consequently, the positive effect also influenced the pitch attitude variation, which was reduced by 39% to 50% compared to the flights without the logic activated.
- The FT envelope was developed based on control and attitude transient effects after the inceptor decoupling. To this end, ratings for 90 test points were assigned by one test pilot according to the transient effects. ROC graphs identified the optimum cutoff points for the severity boundaries (minor/major/hazardous) by analyzing the transient ratings against two variables: RMS control deflection and attitude variation. The intersection of the cutoff points of the variables to the origin was defined as the minor severity area, which corresponds to the optimum area of force threshold envelope.
- Three test pilots assessed the automatic decoupling system to validate the previous results. Only in one case there was a higher TR than the rating expected by the severity area limits, showing a good agreement between ratings and the envelope limits. Also, the Counter Force logic alleviated the control activity and attitude variation in the modified helicopter, resulting in acceptable transients (within the minor severity area) for the FT 20 N and 30 N. The transients following the automatic decoupling, when the FT is set to 40 N, showed significant magnitude of control and attitude (major safety severity region), thus 30 N is indicated as the upper boundary for the FT.
- The inceptor decoupling including the Counter Force activated stabilized the control deflections in case of oscillatory movements of the inceptors, which produced a transitory alleviation of the helicopter attitude and assisted pilots in the controllability. Particularly for 20 N and 30 N, the system was judged as intuitive and effective in most conditions. In general, the inceptor decoupling did not reduce the flying qualities.

8 Design Validation: Pilot Workload and Pilot Acceptance

The chapter presents the evaluations performed for validation of the variable inceptor coupling design. The variable inceptor coupling refers to the configuration 2 (automatic decoupling) and configuration 3 (manual decoupling), which are addressed individually in this chapter. Besides the configurations 2 and 3, the inceptor coupling configuration 1 (coupled without decoupling) is analyzed. The description of the configurations can be found in subsection 4.3.1.

8.1 Test Aim

The aim of these evaluations is to compare the performance of the variable inceptor coupling to takeover control in low level flight against the benchmark, i.e., the permanently coupled inceptors. The configuration 1 (emulation of mechanical cross-cabin linkage) is referred to as the benchmark, because practically all helicopters feature FCS without provision for inceptor decoupling. The comparative analysis explored the following topics:

- Analysis of the FI's performance in takeover control tasks
- Investigation of the inceptor coupling influence on the pilot workload
- Investigation of the inceptor coupling influence on the pilot acceptance

Regarding the first aim, the FI's performance is analyzed through the objective measurement of control and attitude transients in each inceptor coupling configuration.

Concerning the second aim, since the amount of effort and attention that pilot must provide to attain a takeover control maneuver is critical to flight safety, a pilot workload survey is investigated.

Regarding the third aim, the pilot acceptance investigation lays emphasis on the pilot's perceived usefulness and satisfaction to takeover control using the inceptor coupling configurations. A post-study interview containing three questions is applied, providing the opportunity to the pilots to clarify their responses.

8.2 Method – NASA TLX and Acceptance Scale

The criterion to validate the variable inceptor coupling is to be superior to the benchmark for the specific application, i.e., takeover control. To this end, the variable inceptor coupling (configuration 2 and 3) is tested against the permanently inceptor coupling (configuration 1) regarding the effectiveness to alleviate control and attitude transients, to reduce pilot workload, and to be perceived as useful by the experimental pilots.

The Reference Case ($t_{f1} = 0$)

The comparative investigation can quantify the dissimilarities between the configurations, but it cannot indicate how meaningful the difference is. For instance, if the system A is 20% superior to system B for a specific task, then A is preferable to B. But the significance of the improvement is unclear, unless the expected task performance is defined. Therefore, a reference performance for the system validation tests is specified as the best possible case. In this condition, the FI announces the intention to takeover control and the trainee pilot relinquishes control immediately. This condition is referred to as control transfer without interference or $t_{f1} = 0$, since the pilot response time to the action of the FI is minimized to virtually zero.

Typically, the trainee pilot confirms the control transfer by visual, verbal, and occasionally physical feedback. The confirmation procedure can last a few seconds, which may not be available in time-critical conditions, as thoroughly explained in Chapter 3. The $t_{f1} = 0$ condition is possible during the tests because the trainee pilot is expecting the action of the FI.

Therefore, even though the $t_{f1} = 0$ condition is rather unlikely in low level flight, this condition is useful for comparison purposes. The transients in the $t_{f1} = 0$ case can be largely associated to the helicopter dynamics and to the task characteristics, but not to interferences in control. If the variable inceptor coupling attains a performance comparable to the $t_{f1} = 0$, then it can be inferred that the control interference is successfully mitigated, because the interference was not included in the reference case.

8.2.1 Rating Scales and Interview

NASA Task Load Index

The pilot workload was measured using the NASA Task Load Index (TLX). The theoretical rationale for the scale is described by Hart and Staveland [164]. The participants assessed workload from 0 to 100 based on their experience in the takeover control task considering six sub-scales: mental demand, physical demand, temporal demand, frustration, effort, and performance (Figure D.5). The sub-scales descriptions are defined in Table D.3.

The NASA TLX technique also requires participants to complete a series of 15 paired comparisons (i.e., all combinations of the six sub-scales) by identifying which sub-scale contributed more to their experience of workload in the task. A seventh measure of workload (overall workload) is then calculated by multiplying the pairwise weight by the individual sub-scale score, summing across scales, and dividing by 15 (the total weights) [165].

The sub-scales provide a multi-dimensional assessment, which results in the possibility to identify more closely the causes of the workload. NASA TLX has been pointed out as sensitive to changes in workload [165], [166]. The time required to complete the scale is commonly referred to as a disadvantage of the method [167].

Acceptance Scale (van der Laan)

The Acceptance Scale proposed by van der Laan *et al.* [168] was used to assess the pilots' acceptance in terms of attitudes towards the inceptor coupling configurations. This standardized questionnaire identifies usefulness and satisfaction as two dimensions of acceptance through nine bipolar items (Table D.4). The FIs assigned scores from -2 to +2 using the five-point rating scale after each configuration, indicating either rejection or acceptance of the evaluated system. Therefore, zero indicates neither rejection nor acceptance. Positive or negative deviance form zero serves as an indicator of how well the system is accepted.

Five items are related to usefulness (useful, good, effective, assisting, and raising alertness), and four are linked to satisfaction (pleasant, nice, likeable, and desirable). The scores are averaged to each dimension, which indicates the overall acceptance judgment of the participants [168].

Interview

An interview was conducted as a follow-up to questionnaires. The participants were asked to justify their answers to the three closed questions, providing the opportunity to describe their experiences with the evaluated systems. The wording of the questions was reviewed by a psychologist from the DLR's Institute of Flight Guidance before the interview.

The questions are described in Appendix D.8. The first question asks the pilots' opinion about their preference among the tested configurations in terms of safety to takeover control. The second and third questions measures either positive or negative response to a statement, using the five-level Likert scaling method (strongly agree to strongly disagree). The FIs should report their agreement regarding the ability of the inceptor coupling to monitor the trainee pilot (question 2) and to takeover control (question 3).

8.3 Evaluations

8.3.1 Experimental Scenarios

The system validation tests were performed in three experimental scenarios, which were structured to represent possible control transfer problems that may arise during training flights. Takeover control maneuvers are not restricted to instructional situations; however, the trainee-flight instructor situation helps to demonstrate the utilization of the inceptor coupling systems. In all scenarios, the trainee pilot began the experimental trial and the FI performed takeover control maneuvers to avoid ground or obstacle collision. These scenarios are representative of accidents classified as interference with controls, a sub-category of LOC occurrences described in [25]. The scenarios are: approach to helipad, vertical departure, and hover in confined area.

The first scenario consists in the takeover control by the FI after an inappropriate longitudinal input of the trainee pilot during the helicopter flare. The approach to helipad, which was also utilized in the force threshold tests, is defined in the subsection 7.3.1. The complete description of this scenario, including the performance requirements, is shown in the Appendix B.3.

In the vertical departure scenario (Appendix B.4), the trainee pilot takes off upwards from hover to 150 ft AGL. The vertical helicopter motion is necessary due to the height of the obstacle, which is a power transmission tower near the helipad. Between 50 ft and 100 ft, the helicopter drifts laterally towards the electric tower as the consequence of inappropriate lateral inputs (Figure 8.1). The FI shall overpower the trainee pilot to correct the helicopter trajectory. The maneuver is complete when a stabilized hover at 150 ft is achieved.

Lastly, in the hover in confined area (Appendix B.5), the trainee pilot gradually increases the magnitude of control inputs to produce divergent vehicle oscillatory motion in roll or pitch axis. Comparable to the other scenarios, the FI should act on control to takeover and avoid unsafe conditions (Figure 8.1). The first and second scenarios analyze the takeover control in one axis (pitch and roll, respectively), while the third scenario is tested in both axes.

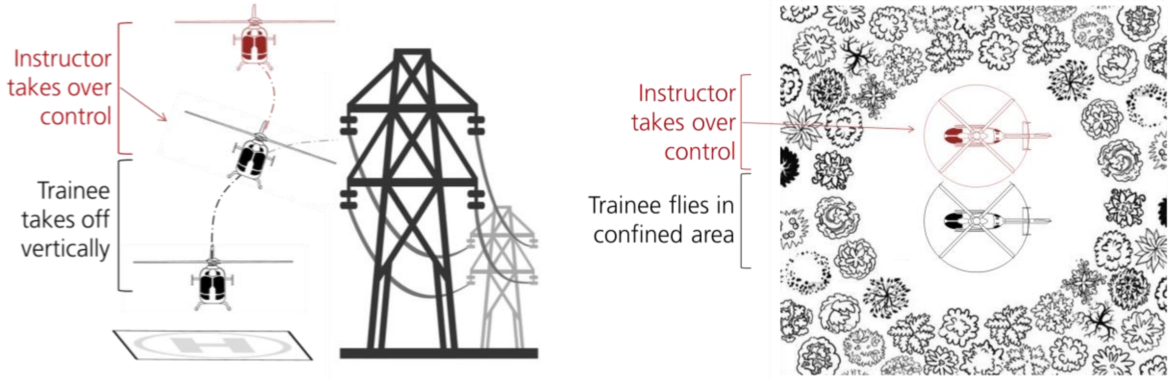


Figure 8.1: Vertical departure (left) and hover in confined area (right) scenarios

8.3.2 Procedures

Five pilots participated in the system validation tests (Appendix C.3). Pilots A, B, G, H and I are not labelled in sequence, because the first two pilots also took part in the first evaluations (SA tests). Pilots A, B and H have similar background, since they are test pilots and flight instructors, besides sidestick experience in helicopter projects. Pilot G is an instructor pilot in German flight training unit, but no sidestick experience. Conversely, pilot I is not instructor, but is familiar with sidestick operation. The characteristics of pilots G and I are considered acceptable for this thesis. Firstly, sidestick familiarity is not considered a requirement to use the system. On the contrary, pilots without sidestick experience may even help to expose difficulties in adaptation using this kind of inceptor, which can be enlightening. Secondly, with regards to instructor experience, even though a takeover control maneuver often occurs as a corrective action in instructional flights, non-instructor pilots should also understand vehicle safety limits and interfere with control in case of direct threat to flight safety.

The pilots, namely FIs, were informed about the scope of the research and the system description before the tests. Special focus was dedicated to familiarize the FIs to the standardized questionnaires. A DLR test pilot (pilot C) was invited to perform as the trainee pilot. Before each evaluation run, three to four practice runs were flown by the FIs. The inceptor coupling configuration was tested randomly among the participants. A total of 100 test points (TP) were completed and recorded. The takeover control tasks were performed in pitch (approach to helipad, 40 TP; and hover in confined area, 20 TP) and in roll axis (vertical departure, 20 TP; and hover in confined area, 20 TP). Due to the deceleration to hover, the approach to helipad is considered the most challenging scenario, therefore more TP were recorded for this scenario.

For the control and attitude transients' analysis, the time of 8 seconds after the FI's interference was adopted as the observation period. This time range was selected because preparation tests indicated that the effects of the transients reduced after this interval. The dependent variable is the inceptor coupling configuration (1, 2 and 3), which are described in the subsection 4.3.1. The force threshold for the configuration 2 is set to 30 N, and the Counter Force function was active. The configuration $t_{f1} = 0$ is used as the reference performance. The helicopter model is the baseline described in 5.1.2.

Following the completion of each maneuver, the FIs assigned ratings using the workload measurement scale, and the acceptance scale. After all the tests, pilots answered an interview including three closed questions (Appendix D.8).

8.3.3 Statistical Analysis

Spectrogram as Time-Frequency Representation

The spectrogram is a time-frequency representation (TFR) to characterize time-varying systems by plotting power versus both time and frequency. The spectrogram is the squared modulus of the Short-Time Fourier Transform (STFT), which is calculated by chirp-z transform and convolves the original signal with a sliding window [169]. In the present thesis, a Hamming window with a 3 second width was selected to provide suitable resolution in both time and frequency, including linear scaling.

The spectrogram is based on the calculations of power frequency, a parameter derived from cutoff frequency[1] that relates the frequency of pilot input with the intensity of this input. The power frequency ($\omega_G(t_i)$) simply multiplies the cutoff frequency at time t_i by the maximum of the power spectral density (max$G_{\delta\delta}(t_i)$) over the frequency range (ω) at time t_i. The metric is then scaled by dividing by 1000, an arbitrary term that is used to scale the parameter for the given problem. Thus, the metric takes the following form [170]

$$\omega_G(t_i) = \frac{\omega_{cutoff}(t_i) max G_{\delta\delta}(t_i)}{1000} \tag{8.1}$$

The multiplication of the time-varying cutoff frequency by the maximum signal power reflects the pilot or vehicle activity, which are evidenced by the spectrogram. Consequently, if the pilot-vehicle system activity is low, the power frequency is reduced. Conversely, high activity (power) corresponds to increased power frequency [169].

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[1] The cutoff frequency uses a power spectral density (PSD) of the pilot's input to provide an estimate of crossover frequency. Time varying cutoff frequency is similar in concept to the classical cutoff frequency, but is computed from TRF instead of PSD.

ANOVA

The so-called "one-way analysis of variance" (ANOVA) is used when comparing three or more groups of numbers. Variations in the evaluated means are expected, because the measurement is normally verified in samples rather than the entire population [171]. The expected variations are named as sampling error. ANOVA identifies if the difference among the groups is greater than the expected to be caused by the sampling error.

The mathematical formulation can be found in [172, p. 68]. The result of this calculation is expressed in a test statistic called the F ratio (designated simply as F), which is the ratio of how much variability there is between the groups relative to how much there is within the groups. The general form of writing the result of a one-way ANOVA is as follows:

$$F(df_b, df_w) = F_{ratio}, p\ value \tag{8.2}$$

where df_b = degrees of freedom between groups, df_w = degrees of freedom within the groups.

A significant *p*-value (usually taken as $p < 0.05$) suggests that at least one group mean is significantly different from the others.

Tukey's HSD Post Hoc Test

Since ANOVA cannot specify which configuration differed, the *post hoc* Tukey honestly significant difference (HSD) test is carried out as a multiple comparison analysis. *Post hoc* tests are designed for situations in which an overall statistically significant difference in group means has been verified (i.e., a statistically significant one-way ANOVA result). Tukey HSD test uses a number that represents the distance between groups to compare every mean with every other mean. The procedure for the pairwise means comparisons applied by this test is described in [172, p. 98]. The result of the *post hoc* test is reported by the significant *p*-value of each comparison.

8.4 Results and Discussion

8.4.1 Results

This subsection is divided by the following parts: analysis of transients, pilot workload, and pilot acceptance. An interview complements the standardized questionnaire in the pilot acceptance part.

Analysis of Transients

An in-depth quantitative analysis of the takeover control effects was conducted. The FIs performed each takeover control task to avoid obstacle collision using the inceptor coupling configurations. The acceptability of the variable inceptor coupling (configurations 2 and 3) was determined through the analysis of the attitude and control variations influenced by the inceptor decoupling.

To illustrate the investigation of these parameters, Figure 8.2 depicts the plots for the configuration 1 and 2 respectively.

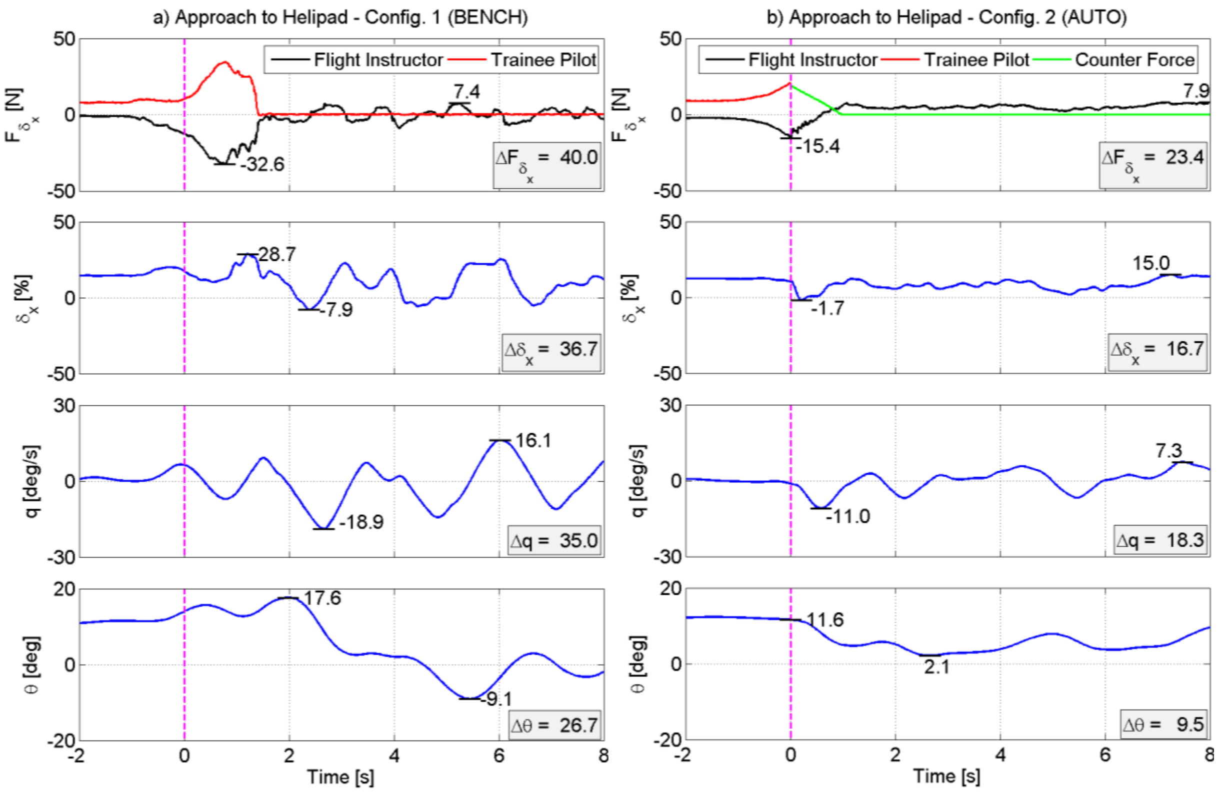

Figure 8.2: Takeover control in the configuration 1 (a) and 2 (b); approach to helipad scenario; pilot A

In these examples, time = 0 represents the moment of the takeover control. The results indicate higher control variations in the case of inceptor system without decoupling (configuration 1, $\Delta\delta_x$ = 36.7%) compared to the automatic decoupling (configuration 2, $\Delta\delta_x$= 16.7%). It should be noted that some variation was required to comply the task, since the FIs should not only adjust the pitch attitude, but also bring the helicopter to hover. By raising the collective lever, the helicopter model induces variations in pitch that should be compensated by FIs.

The boxplots of the helicopter attitude and control deflection variation are depicted in Figure 8.3 (approach to helipad), Figure 8.4 (vertical departure), and Figure

8.5 (hover in confined area). The first two scenarios analyzed the takeover control in pitch and roll axis respectively, and the last one was tested in both axes.

The blue boxplots represent graphically the data through the inner quartiles (25-75%), and the horizontal red lines indicate the median values. The horizontal black lines at the end of the dashed lines specify the maximum and minimum values, which is also equivalent to the lower and upper quartiles. The green band in Figure 8.3 to Figure 8.5 denotes the second and third quartiles of the control transfer without interference ($t_{f1} = 0$), which was explained in the method subsection (8.2). As such, the boxplots of the tested configurations and the best possible case ($t_{f1} = 0$) can be directly compared.

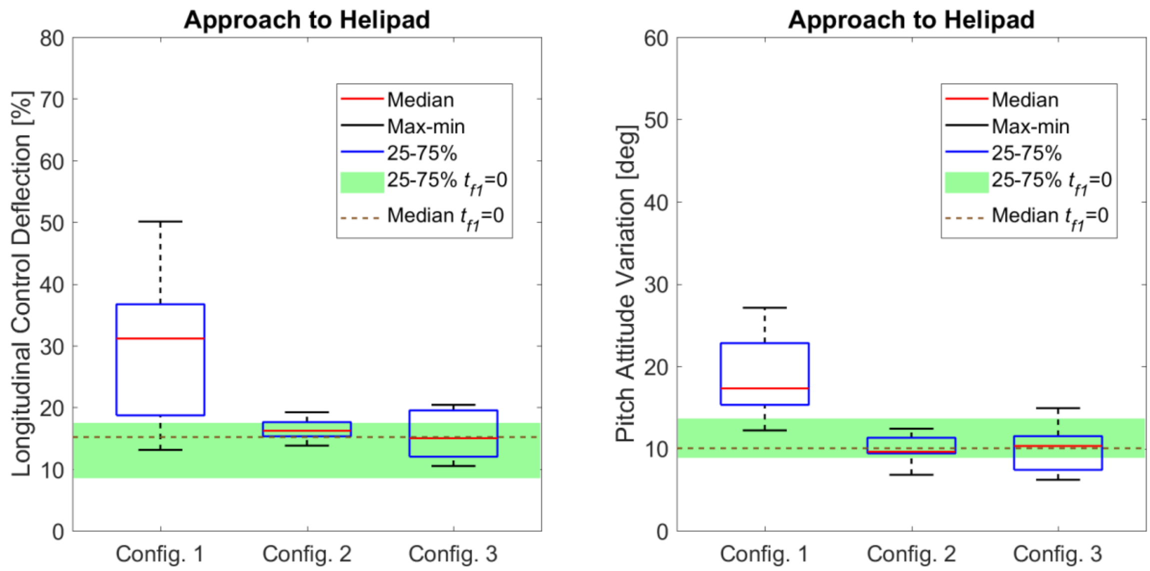

Figure 8.3: Boxplot of attitude and control deflection in approach to helipad

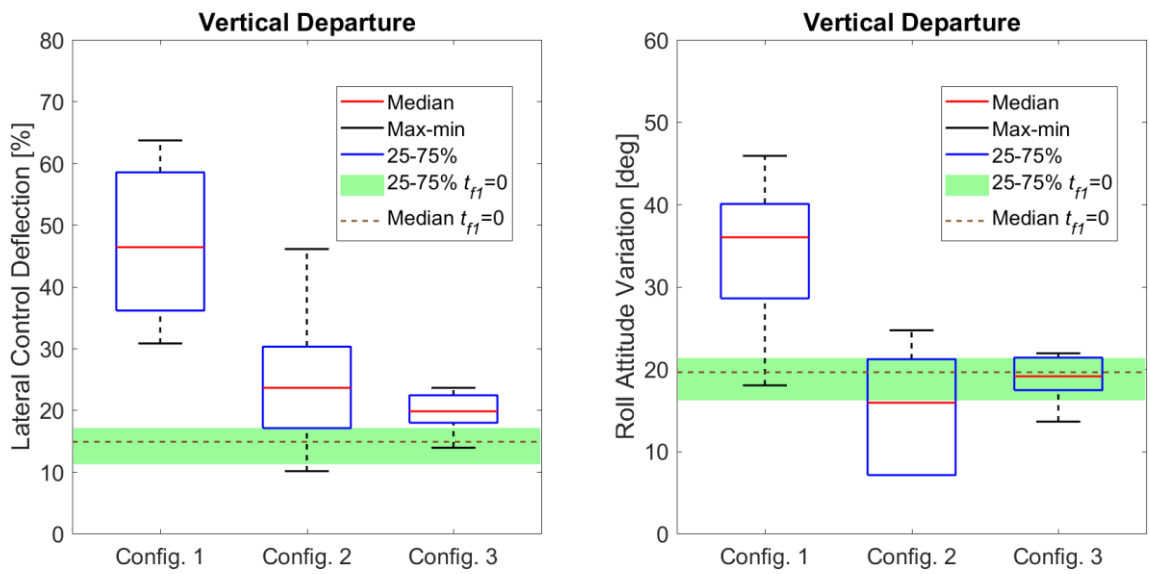

Figure 8.4: Boxplot of attitude and control deflection in vertical departure

The dashed brown line shows the median value of the $t_{f1} = 0$ case.

All of the boxplots relative to configuration 1 are above the green area. The result confirms that even in case of a brief interference in control (1.5 seconds on average), the control activity and helicopter motion can be significantly affected.

In all scenarios, the configuration 1 (BENCH) was characterized by difficulties to recover the helicopter as a result of the control overshoot (short-term effect). The pilots typically reacted by increasing the control activity (i.e., applying larger inputs). This is a direct consequence of the unpredictability of the force-control characteristics, due to the control handover following force-fight condition of 1.5 seconds. The attitude variations

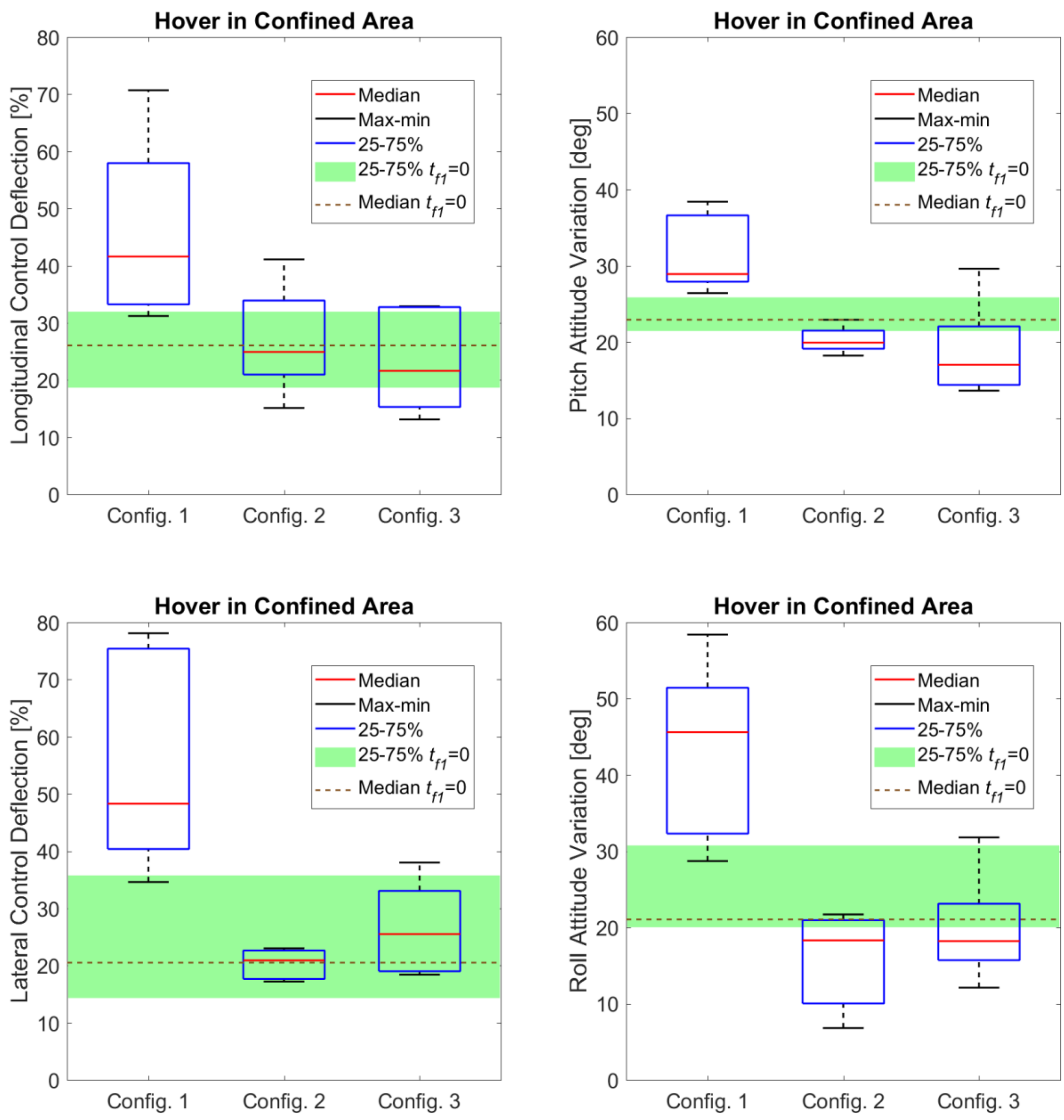

Figure 8.5: Boxplot of attitude and control deflection in hover in confined area

in the mid-term response can also be attributed to the control interference.

Configurations 2 and 3, in most of the control deflection graphs (left side of the boxplot figures), were comparable to the control transfer without interference. The exception is the vertical departure, which is right above the reference green area. Even in this case, the helicopter attitude oscillations were not notably affected, since the attitude variations are corresponding to the best case. In all scenarios, at least one priority configuration achieved improved result in comparison with the $t_{f1} = 0$ case for the attitude graphs (right side), which can be identified by the boxplots below the green band.

It should be noted that, in configurations 2 and 3, the trainee pilot initially ignored the verbal command to transfer control. The introduction of the pilot response time (i.e., the reaction time to relinquish inceptors) produced a momentary discordant attitude of the trainee pilot, which motivates the FIs to activate the inceptor decoupling when it was available. Even with the discordant attitude of the trainee pilot, an improvement of the configurations 2 and 3 compared to configuration 1 is readily apparent.

The boxplots showed the amplitude of the control inputs and the consequences to helicopter attitude. The spectrogram can further analyze the pilot control and helicopter response activity the during the takeover control tasks. To this end, two pilots (FI) are selected to illustrate the distinctions between the various runs. Pilot G plots represent the action of takeover control in roll axis, and pilot H plots illustrate the takeover control in pitch axis; both cases in the scenario of hover in confined area.

Figure 8.6 to Figure 8.11 show the input and output spectrograms for six example cases, corresponding to the use of inceptor coupling configuration 1, 2 and 3 by the two selected FIs. The time histories consisting of inceptor force, stick position, attitude rate and attitude angle for each of the example cases are included for completeness from Figure E.3 to Figure E.8.

The time axis in the spectrograms was adjusted to indicate the takeover control moment at time = 4 s. The analysis is extended by 10 s after the FI's intervention. Plot scales are constant within runs for the same axis for ease of comparison. The peaks in all spectrograms are resulting from the abrupt interference on control by the FI to correct the inappropriate trainee input.

For the roll axis (pilot G), Figure 8.6 shows the initial peak due to the takeover maneuver of 0.05 Hz at time = 4 s, followed by a second peak of 0.45 Hz at time = 6 s. This sequence of control inputs at high activity is the control overshoot, which leads to the aircraft response in a frequency peak of 0.65 Hz (time = 6.5 s in the right side of

Figure 8.6). Since the task is accomplished near obstacles, the pilot should act on controls to stabilize the helicopter as soon as possible. The increased control activity in the end of the period reveals that the aircraft is still not in hover position, and requires new input adjustments.

The spectrogram of the configuration 2 shows moderate activity in the

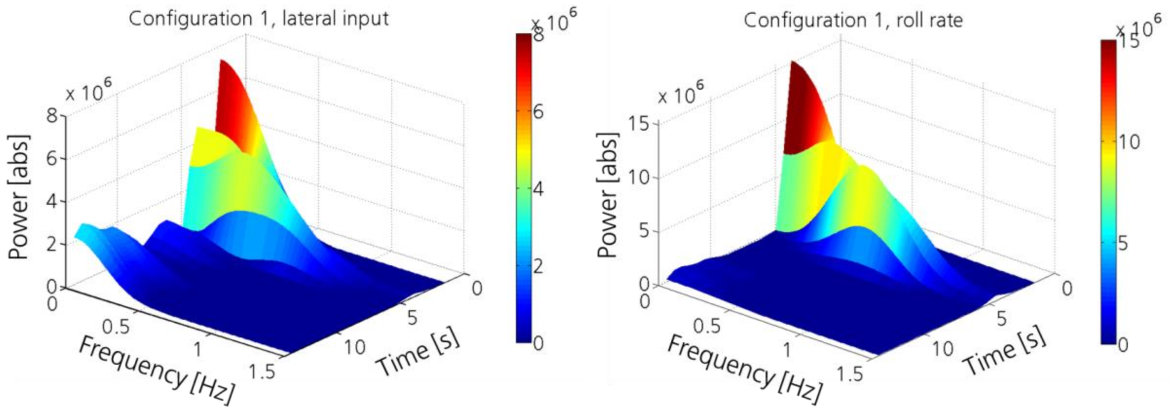

Figure 8.6: Spectrogram of takeover control in roll axis, pilot G, configuration 1

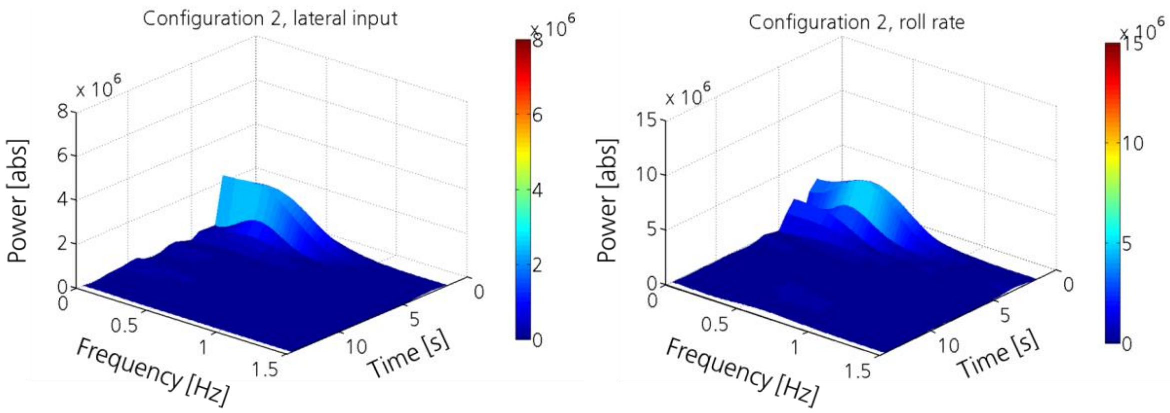

Figure 8.7: Spectrogram of takeover control in roll axis, pilot G, configuration 2

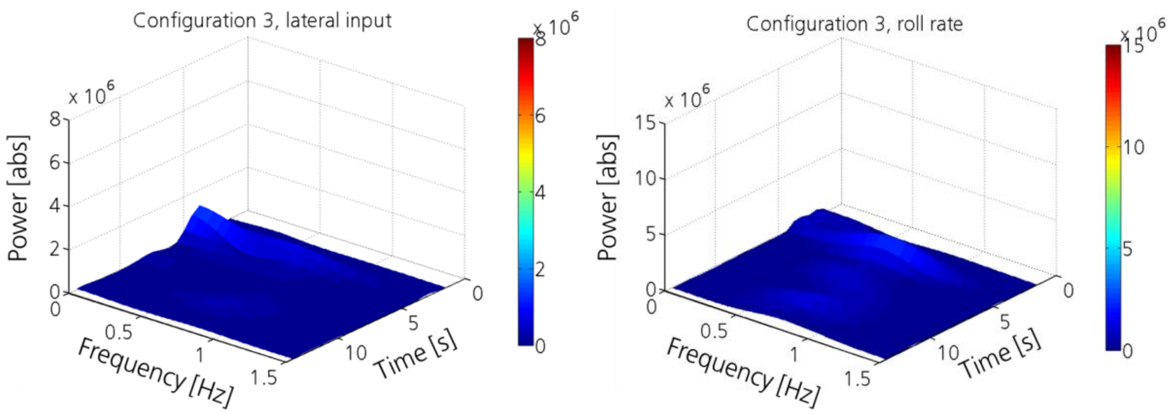

Figure 8.8: Spectrogram of takeover control in roll axis, pilot G, configuration 3

decoupling moment (Figure 8.7). In the rest of the run, minimal control power is identified. The frequency peak of the vehicle response is reduced in comparison with the configuration 1 (0.40 Hz versus 0.65 Hz). Even less stick activity is verified in the configuration 3 (Figure 8.8). The FI was prepared to takeover control and deactivated the trainee pilot before the input error could increase. Frequency peaks of 0.70 Hz and 0.60 Hz produced marginal roll rate effects, since the input magnitude was low.

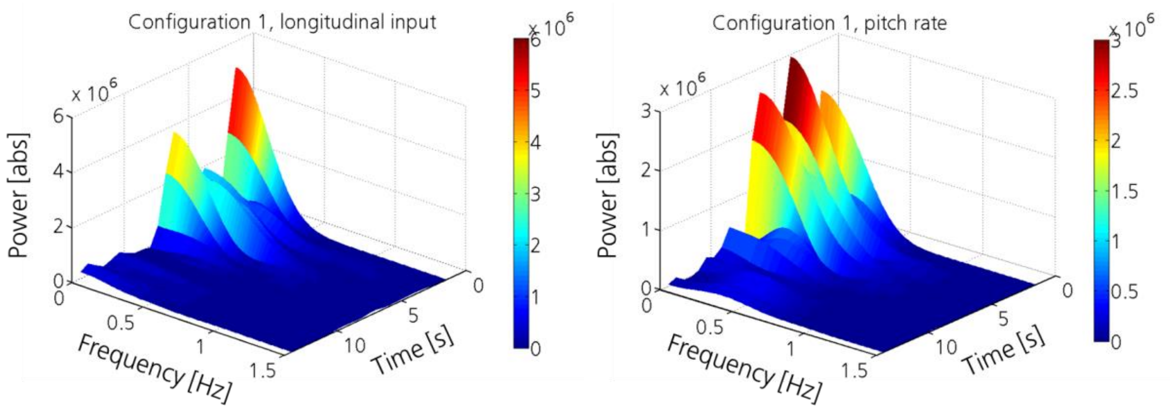

Figure 8.9: Spectrogram of takeover control in pitch axis, pilot H, configuration 1

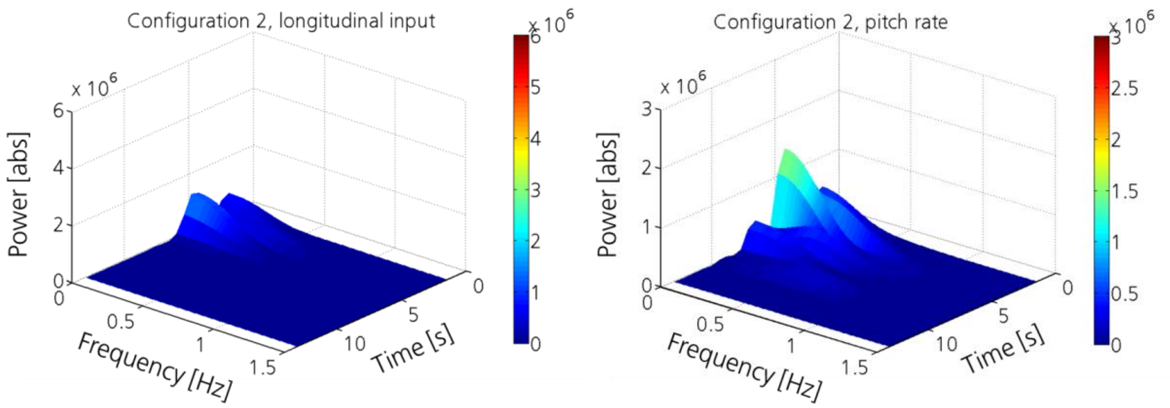

Figure 8.10: Spectrogram of takeover control in pitch axis, pilot H, configuration 2

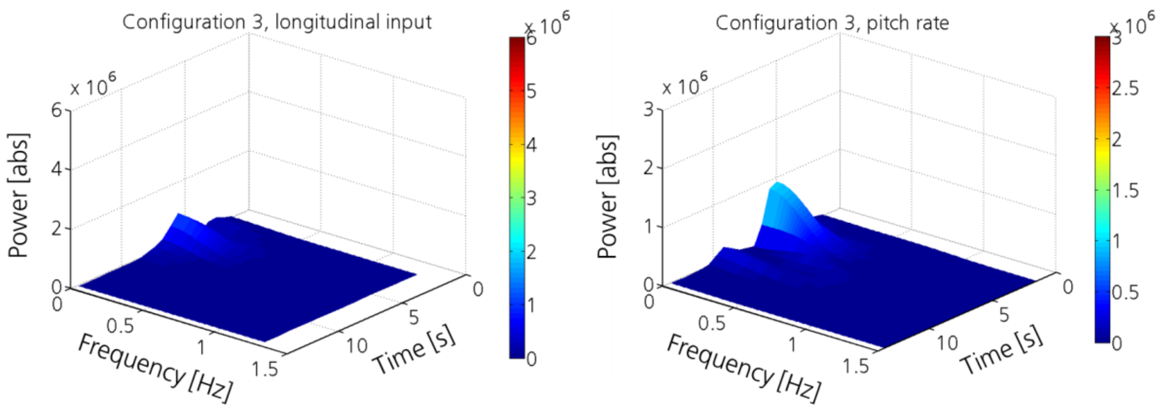

Figure 8.11: Spectrogram of takeover control in pitch axis, pilot H, configuration 3

For the pitch axis (pilot H), in the configuration 1 (Figure 8.9), the control activity at low frequencies (between 0.05 Hz and 0.30 Hz) induces significant vehicle motions. The right side of the Figure 8.9 shows the pitch rate oscillatory response until time = 10 s.

The configuration 2 and 3 are characterized by low activity through the majority of the run (Figure 8.10 and Figure 8.11). The increase in pitch rate power response until time = 6.5 s reflects the vehicle response to the pilot input during the takeover control. The input frequency peaks are lower compared to configuration 1 (between 0.05 Hz and 0.20 Hz).

The spectrogram also indicates differences in the control strategy between the pilots. The input power of pilot H is focused mainly at low frequency. Pilot G exhibits more activity in a higher frequency range throughout the run, as shown by the ripples in the spectrogram.

A direct comparison of the magnitude cannot be drawn, due to the differences in the control sensitivity of the lateral and longitudinal input. But the comparisons between the runs of the same pilot suggest a reduced control activity of the configuration 2 and 3 compared to the configuration 1, which shows the impact of the inceptor decoupling systems.

For the same pilots and scenarios, the control transfer without interference ($t_{f1} = 0$) produced fairly similar results to configurations 2 and 3. The time histories and spectrograms of this case ($t_{f1} = 0$) are included from Figure E.9 to Figure E.12.

Pilot Workload

The pilot workload was measured using the NASA TLX. Figure 8.12 illustrates the variation in the overall workload score through subjective opinion of five FIs. The higher workload levels are associated to the configuration 1 (mean value 61.9). The inceptor coupling including decoupling functions showed workload reduction of 29% (AUTO) and 34% (PUSH) in comparison with the first configuration.

The overall workload scores were examined with ANOVA to determine whether or not there is a statistically significant difference between the configuration means. The analysis yielded statistically significant variation among the inceptor coupling configuration means, $F(2,12) = 9.50$, $p < 0.03$ (Table E.21).

Since ANOVA cannot specify which configuration differed, the *post hoc* Tukey HSD test was carried out as a multiple comparison analysis (Table E.22). This test showed that the configuration 1 (BENCH) differed significantly if compared to the others inceptor coupling configurations. Conversely, the configurations 2 and 3 were not significantly different in case of pairwise comparison. The similar workload scores of the last two configurations support the quantitative results presented in the previous subsection.

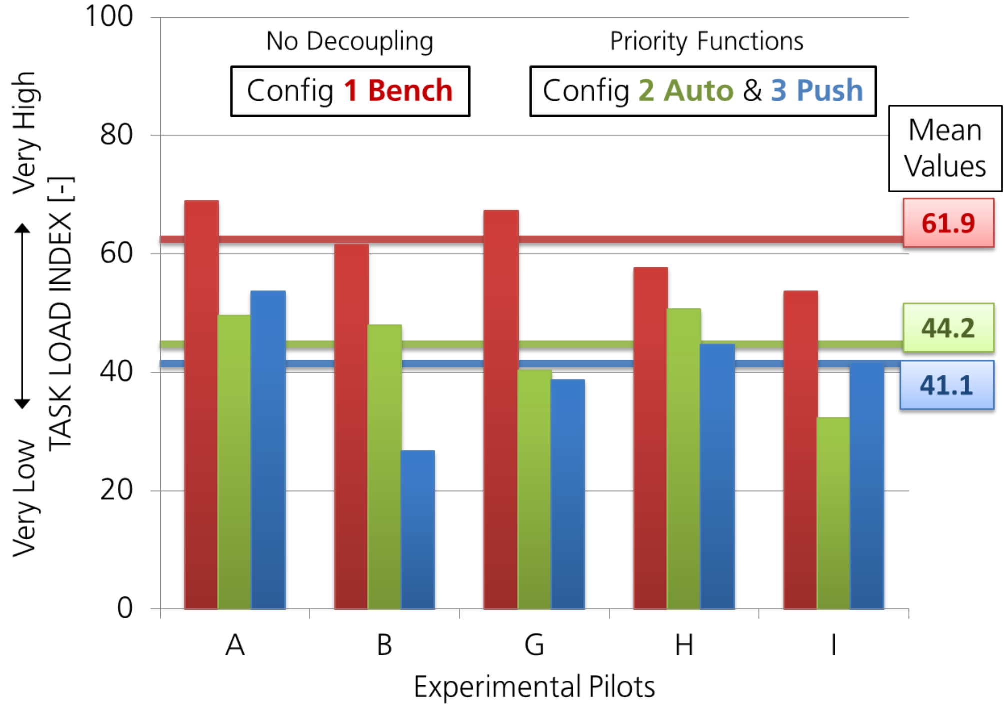

Figure 8.12: Overall NASA TLX workload per pilot

The pushbutton configuration was assigned as the lowest overall workload option by majority of the FIs (pilots G, B and D). The takeover control without control interference ($t_{f1} = 0$) was also tested. This condition resulted in overall workload of 45. It represents a fairly equivalent pilot workload in comparison with the configurations 2 and 3.

Figure 8.13 presents the mean values of all pilots for the six NASA TLX sub-scales for each inceptor coupling configuration. The data can provide valuable information about the differences between the tested inceptor couplings. The significant temporal demand scores may be attributed to the time-critical task, where a timely intervention of the FIs was needed. The physical demand was relatively low for configuration 3 (PUSH), due to the fact that the FIs could push the button to avoid force fight between the pilots. In the case of configuration 2 (AUTO), a rapid force-fight condition was necessary to reach the force threshold and trigger the decoupling. In configuration 1 (BENCH), physical demand, temporal demand and effort were the highest scores.

The boxplot of the NASA-TLX overall workload scores for the three configurations is shown in Figure 8.14. The green area indicates the inner quartiles of the control transfer without interference, and the dashed brown line the median value.

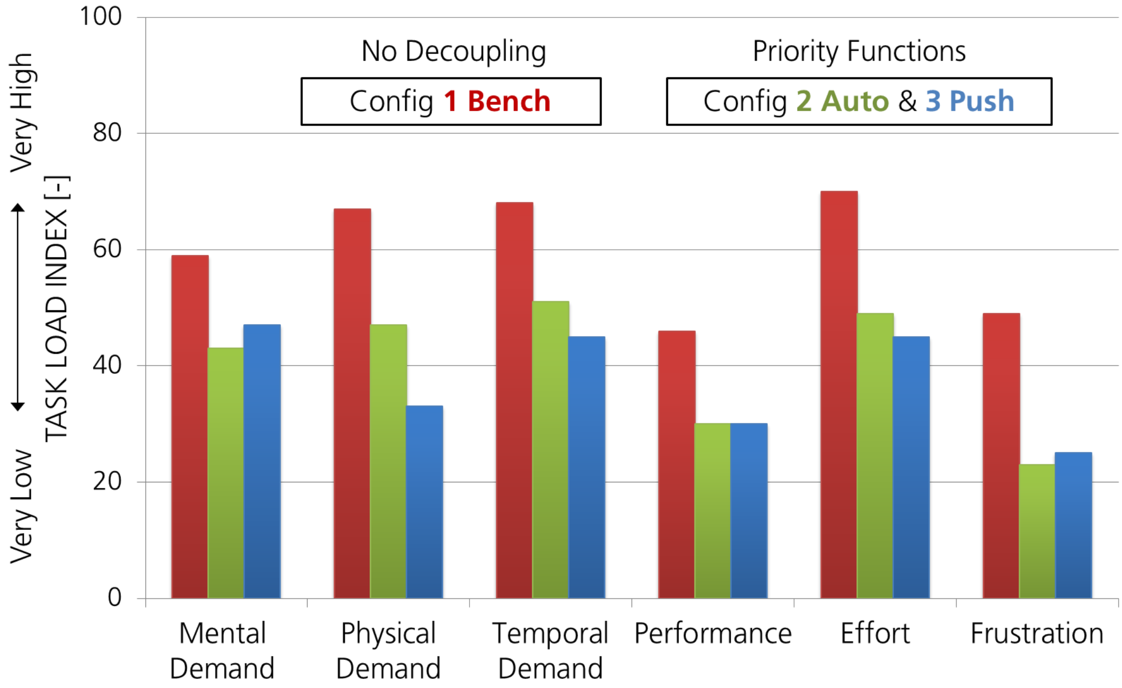

Figure 8.13: NASA TLX workload with respect to subscales

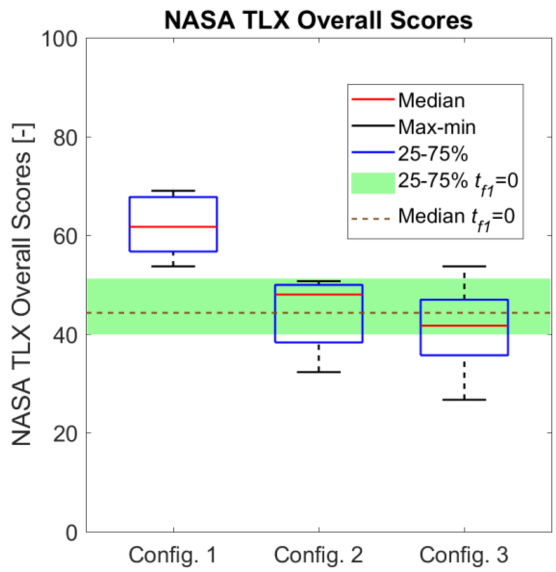

Figure 8.14: NASA-TLX overall workload scores

The NASA TLX boxplot of the configuration 1 is outlined entirely above the third quartile (75%) of the reference case. The TLX boxplots of configurations 2 and 3 on the NASA-TLX are particularly close to the interquartile range of the control transfer without interference. However, the first quartiles of the configurations 2 and 3 are lower than the reference, i.e., an enhanced performance in terms of perceived workload level. The overall workload is not expected to be low, due to the fact that the takeover control action near the ground/obstacles requires minimum mental and temporal demand of pilots.

Pilot Acceptance

The van der Laan Acceptance Scale [168] was used to assess the pilots' acceptance in terms of attitudes towards the inceptor coupling configurations. The FIs assigned scores from -2 to +2 in the standardized questionnaire (Appendix D.7) to indicate either rejection or acceptance of the system. Therefore, positive or negative deviance form zero serves as an indicator of how well the system is accepted.

The boxplots for the ratings of the two dimensions are shown in Figure 8.15. The green area corresponds to the maximum and minimum values of the control transfer without interference ($t_{f1} = 0$). Table E.23 presents the mean ratings and standard deviations of the individual acceptance items and Table E.24 shows results with respect to pilot rating for each inceptor coupling configuration.

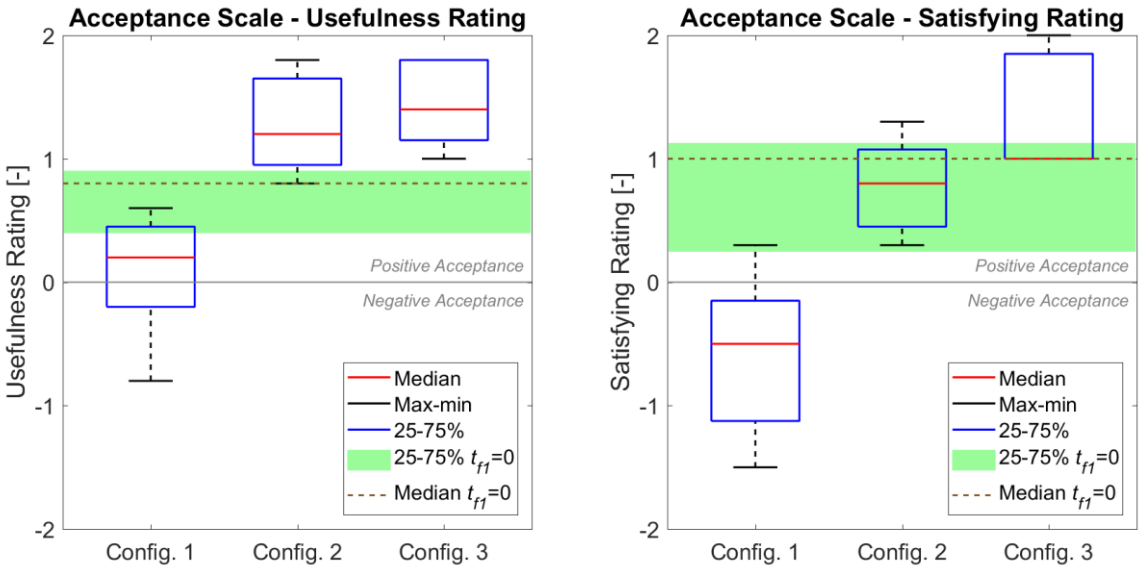

Figure 8.15: Acceptance rating scales

Regarding the usefulness scale, the configuration 1 (BENCH) results indicate that pilots showed a nearly neutral reaction for the given task. It should be noted the one of the five items of the usefulness scale was well rated. The 'raising alertness' mean value was rated as 1.6, indicating that the emulation of the mechanical linkage increased the awareness of the pilots in case of control interference. Even though the approval on the alertness rating, this was the only positive item of all five available.

While the pilots' ratings varied between -0.8 and 0.6 for the configuration 1, the minimum and maximum ratings are equal to 0.8 and 1.8 for the configuration 2, and 1.0 and 1.8 for the configuration 3. Still concerning the usefulness dimension, the difference between the configurations can be confirmed in the statistical analysis. Following the ANOVA results (F (2,12) = 14.0, p < 0.01), the *post hoc* Tukey HSD test showed that the acceptance ratings in configuration 1 differed significantly at p < 0.01

in the pairwise comparison with configuration 2 and 3 (Table E.25 and Table E.26). The configurations including decoupling methods are statistically equivalent to each other. Thus, pilots rated the configurations 2 and 3 as the most useful ones (+1.3 and +1.4, respectively), and the improvement against the configuration 1 is statistically significant.

In the satisfying dimension, the ANOVA results are similar to the usefulness score ($F\,(2{,}12) = 17.6$, $p < 0.01$). The configurations are statistically different at $p < 0.05$ in the three possible pairwise comparisons performed by the *post hoc* tests (Table E.25 and Table E.26). Conclusions about the relation of the two acceptance dimensions can be found in Figure 8.16. The combined plot of usefulness and satisfying scale ratings presents a dashed line, which can be seen as the agreement between the acceptance sub-scales. Configuration 3 is placed on the dashed line. It can be stated that pilots ranked the usefulness and satisfaction in the same proportion. But the automatic decoupling (configuration 2) is above the dashed reference line, meaning that pilots considered the system more useful than the experienced satisfaction level.

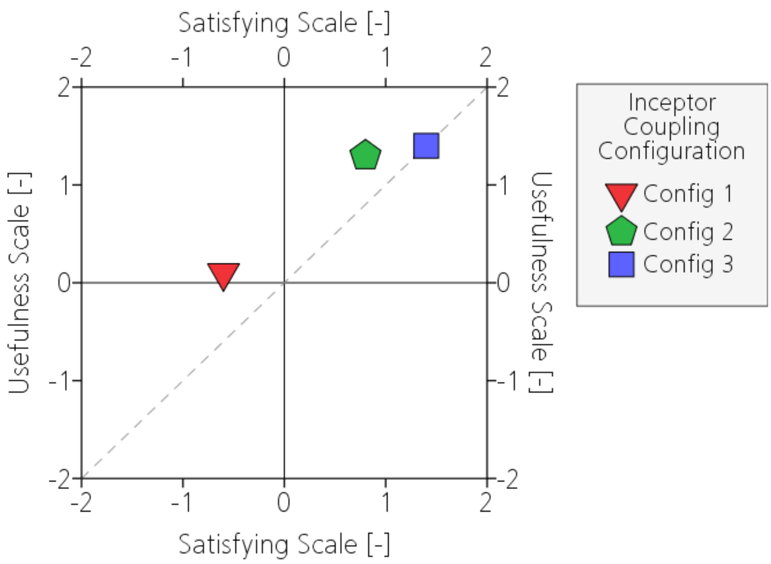

Figure 8.16: Combined plot of usefulness and satisfying rating scale (mean values)

It is notable that the configuration 1 (permanently coupled inceptors) was rated as neutrally useful, since this system is similar to the inceptor coupling in actual helicopters. It should be emphasized that the usefulness ratings are not focused on the general application, but are linked to the proposed tasks. An interview tried to identify the essence of the above mentioned ratings.

Interview

The FIs answered three closed questions (Appendix D.8), and had opportunity to explain their responses. The answers are influenced by all the tests listed in this chapter, which were completed by the time they were interviewed (post-study survey). The answers of each pilot are summed up in the Table E.27 (question 1), Table E.28 (question 2), and Table E.29 (question 3). The summary of the answers is included here.

Question 1: *In terms of flight safety, how do you order the inceptor coupling configurations from 1 to 3 for the task of takeover control?*

The FIs were oriented to rank the configuration from 1 (highest) to 3 (lowest) according to their perception of which variable contributes the most to safety when takeover control were attempted. The number of questions for each classification (highest, intermediate, or lowest safety relevance) is shown in the Table 8.1. No pilot elected the configuration 1 as the highest relevant system, 2 pilots suggested that the configuration 2 was the best option, and 3 pilots informed that configuration 3 was the preferred one.

Table 8.1: Answers to question 1 of the interview

#1: Safety relevance to takeover control [number of answers]				
Dependent Variable		Highest relevance	Intermediate relevance	Lowest relevance
Safety Relevance	Config. 1	0	0	5
	Config. 2	2	3	0
	Config. 3	3	2	0

The pilots considered the takeover control maneuver using the configuration 1 as realistic and unpleasant. One FI added that the attentiveness about the inappropriate input of the trainee pilot by the FIs was high in the simulator (FI was expecting the error), which was insufficient to compensate the helicopter oscillations. It was asserted that this configuration exposes the lack of FI’s control authority, and an alternative to the virtual rigid coupling is desirable.

The configuration 2 was generally deemed to be more intuitive than the other configuration options. According to one pilot, the automatic decoupling represents a more natural reaction of the pilots to correct inappropriate inputs. Pilots expressed concerns about the brief force fight necessary to trigger the inceptor decoupling, since it can cause minor oscillations. This configuration was judged as quick and useful in a number of conditions.

The configuration 3 was considered reliable in case of delayed reaction or high workload. Although it can be mentally demanding to define the moment of the manual decoupling, it can avoid the force fight condition. The activation of decoupling button was not trivial to one pilot, since he constantly used the same finger (thumb) to release the trim during the tasks. In general, the manual decoupling was referred to as fast and effective.

Question 2: *From the instructor pilot perspective, the electronic inceptor coupling provides the ability to monitor the performance of the trainee pilot using the configuration 1.*

The mean value for the five FIs is indicated in Figure 8.17, which is calculated converting the pilot's agreement answers to values. Thus, the 'strongly disagree´ is equivalent to -2, the answer 'strongly agree' corresponds to 2, and the options in-between are numbered accordingly. In brief, pilots affirmed that the configuration 1 helped to monitor the performance of the trainee pilot. One pilot communicated that the reduced control travel of the sidesticks in comparison with the conventional long pole can affect the information perceived by the instructors.

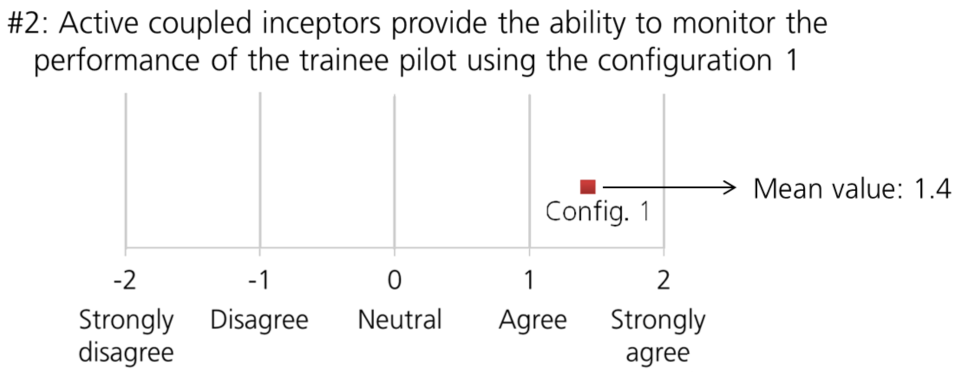

Figure 8.17: Mean value for the question 2 of the interview, 5 experimental pilots

Question 3: *In case of inappropriate inputs in low level training flight, the variable inceptor coupling system can assist the instructor pilots to takeover control considering the possibility to use the…configuration 2/configuration 3.*

The mean values for the five FIs are indicated in Figure 8.18, which were calculated as described in question 2. The configuration 2 is associate with positive comments of intuitive, quick, and no button concerning. The configuration 3 is related to remarks of clean, fast, reliable, and predictable.

A positive aspect of one configuration can be mirrored as the negative aspect of the other. Configuration 2 is notable to trigger the decoupling automatically, therefore relieving the pilot of button concern, but is also considered intrusive because the logic of the computer is deciding the decoupling moment. Conversely, the configuration 3 provides to the pilot the authority to decide when is the appropriate moment to decouple inceptors. However, this button shall be used eventually, and the pilot still has to find the button position in the cyclic lever in time-critical conditions, when every second is decisive to flight safety.

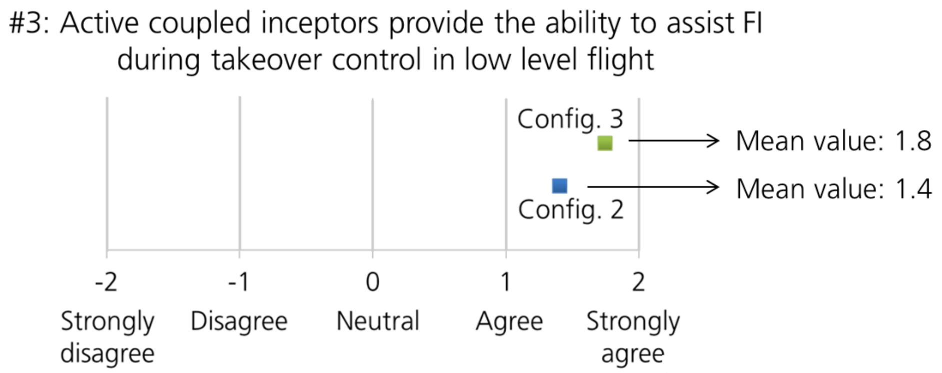

Figure 8.18: Mean values for the question 3 of the interview, 5 experimental pilots

8.4.2 Discussion

The analysis of the attitude and control transients indicated that the permanently coupled inceptor can lead to helicopter oscillations, which might be critical in scenarios near the ground and surrounded by obstacles. In the proposed scenarios, the FIs could efficiently interrupt the interference of the trainee pilot on control through the decoupling functions of the priority configurations (2 and 3), whereby the takeover maneuver was performed without significant overcontrol. The mitigation of the oscillations can be attested by the comparable performance of the decoupling configurations with the control transfer without interference.

The possibility to decouple controls not only reduced the amplitude of the control used in the tasks, but also the control activity was alleviated. When the decoupling was present, the pilots used a control strategy that enables faster stabilization of the helicopter compared to the option without decoupling (configuration 1).

The tasks proposed a natural reaction of the trainee pilot (1.5 seconds), which increased the overall workload for the case without decoupling. The decoupling possibility minimized the trainee pilot interferences, which caused a noteworthy workload reduction. Pilots asserted that the priority functions were reliable, predictable, simple and easy. Consequently, experimental pilots successfully performed the takeover control maneuver with lower levels of perceived workload.

The positive scores in terms of usefulness indicate that changes in design to allow the manual and automatic decoupling met the pilot's expectations. The decoupling methods, as presented in configuration 2 and 3, were useful to compensate the trainee response time during control transfer. The interview confirmed that pilot's attitudes are largely optimistic about the implementation of the novel decoupling configurations, since it is deemed relevant to increase the safety of dual pilot helicopter operations.

8.5 Concluding Remarks

The main results addressed in this chapter are:

- The inceptor coupling configuration without decoupling was tested as 1.5 seconds response time of the trainee pilot to relinquish inceptors. In this case, when the inceptor decoupling was not possible, interferences with control during the takeover maneuver caused control overshoot (short term effect) and difficulty to recover the helicopter control (mid-term effect). Moreover, this condition led to increased attitude transients, inceptor deflections and pilot workload.
- Coupled inceptors including manual and automatic decoupling functions were tested under the same conditions. The takeover maneuvers were performed in low level flight without overcontrol through both inceptor decoupling methods.
- The possibility to decouple controls not only reduced the amplitude of the control used in the tasks, but also alleviated the control activity. When the decoupling was present, the pilots used a control strategy that enables faster stabilization of the helicopter compared to the option without decoupling.
- Pilots considered the priority functions reliable, predictable and easy. Consequently, experimental pilots successfully performed the takeover control maneuver with lower levels of perceived workload. The priority functions mean values showed workload reduction of 29% (automatic inceptor decoupling) and 34% (manual inceptor decoupling) in comparison with a configuration without inceptor decoupling.
- The control transfer without interference was performed, whereas both pilots applied maximum attentiveness and immediately collaborated for success of the task. The results of this perfect interaction to takeover control were comparable to the cases including decoupling functions conditions in terms of control attitude transients, inceptor deflections and pilot workload.
- The decoupling functions were well accepted by the experimental pilots. Positive ratings in usefulness and satisfying scales were assigned. The priority configurations (both automatic and manual inceptor decoupling) were considered very useful, and manual decoupling achieved the highest satisfaction level between the configurations tested.
- Due to the flexibility and superior performance of the decoupling methods against the design without decoupling means, a variable inceptor coupling

configuration that includes decoupling functions was considered validated to assist pilots during takeover control in low level flight.

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9 Conclusions and Future Works

The purpose of the current thesis was to investigate the possibility to assist pilots during takeover control in dual pilot helicopters. According to safety reports, takeover control maneuvers may lead to loss of control accidents due to control interference of pilots, especially during training flights. Therefore, an approach to designate the primary set of flight controls using a decoupling method, as a takeover button or a priority algorithm, was pursued to resolve the control conflict between the pilots. In the light of the safety challenge, the programmable nature of active coupled inceptors provides feasible conditions to implement a control prioritization to mitigate this category of accidents. The active technology allows the programming of decoupling functions without any additional mechanical system of separation for the cross-cabin linkage, which is relevant to the required aeronautical reliability in the certification process.

The completeness of the research investigation was attained through analysis of two main problems. Firstly, the ability of active coupled inceptors to provide understandable feedback through the inceptors and to contribute positively to the situational awareness of helicopter pilots was unknown. It should be noted that this is a precondition to perform timely takeover control maneuvers. Secondly, there was uncertainty regarding the impact of a decoupling system on the control deflection and the helicopter attitude during takeover control maneuvers using electronically coupled inceptors.

These issues were structured in three set of evaluations (described in Chapter 6 to 8), on which the investigation of the main scientific question is based. The research resulted in the following findings, which are addressed by the corresponding contribution. The sub-aspects of the scientific question (SQ) can be found in the section 0.

Research contribution 1 (SQ1): *validate an inceptor coupling system in active sidesticks for helicopters.*

This thesis has demonstrated, for the first time, the ability of the AIS to support the helicopter FI to monitor the performance of the trainee pilot. To this end, the contribution of the inceptor coupling system to the pilot awareness was quantified by the comparative analysis of coupled and uncoupled inceptors. The SA tests have identified that all three test pilots consistently achieved higher SA scores using the coupled configuration compared to the uncoupled counterpart (differences of 13% to 26% in favor of the coupled configuration). The average difference of 19% represents a statistically significant increase in the SA.

The electronically coupled inceptors showed higher influence on the ability to project future states of the helicopter (SA level 3). The extra information conveyed by the force feedback of the coupled inceptor provided the anticipatory responsiveness, which proved to be meaningful in flights near obstacles.

Overall, the force feedback contributed positively to the FIs in the task of monitoring the performance of the trainee pilot. All pilots indicated that visual cues in the uncoupled design could not compensate the force feedback provided by the electronically coupled inceptors. Also, pilots considered the electronic coupling of the active inceptors alike the true mechanical linkages across the cabin. These findings enhance the understanding that the electronic cross-cabin coupling can convey the information necessary to the helicopter pilots to act timely in low-level flights.

Research contribution 2 (SQ2): *propose a method to mitigate the attitude oscillations during takeover control by reducing the control activity through adaptive fading force logic in automatic inceptor decoupling.*

The empirical findings in this thesis confirmed the possibility to mitigate control overshoots during the automatic inceptor decoupling through the implementation of a force fading logic (Counter Force). The logic showed to be both effective to alleviate control deflections and attitude oscillations, and helpful to stabilize the helicopter attitude in case of PIO. Even in case of poor handling qualities (HQ level 3), the helicopter indicated no tendency to lose control due to the automatic inceptor decoupling, showing the ability to assist pilots by decoupling inceptor to prioritize one control station without degrading the flying qualities. These findings are meaningful in the implementation of a time-critical function to be used near the ground.

Research contribution 3 (SQ2): *propose a methodology to develop a force threshold envelope in automatic decoupling systems for electronically coupled active sidesticks.*

One significant finding to emerge from this thesis is the development of the FT envelope to support the implementation of the automatic decoupling system. To this end, 90 TP were used to assign transient ratings, which were plotted against two variables: RMS control deflection and attitude variation. The optimum area of the enveloped is associated to the safety severity area classified as ‘minor’.

Three test pilots validated the results through the satisfactory agreement between pilot ratings and the envelope limits. The FT range was defined in the interval between 20 N and 30 N, which is useful to avoid unintentional decoupling (minimum FT) and excessive attitude oscillation (maximum FT). In general, the inceptor decoupling did not reduce the flying qualities. If the differences regarding the force feel characteristics are considered, the FT envelope is readily applicable for different control types (pitch, roll and heave).

Research contribution 4 (SQ3): *prove the ability of the active sidesticks to support the flight instructor to takeover control in low level flight.*

The conditions of the accidents classified as control interference were tested in the simulator using either inceptor coupling configuration with or without decoupling means. The experiments confirmed that interferences with control during the takeover maneuver without inceptor decoupling, tested as 1.5 seconds response time of the trainee pilot to relinquish inceptors, caused control overshoot (short term effect) and difficulty to recover the helicopter control (mid-term effect). Moreover, this condition led to increased attitude transients, inceptor deflections and pilot workload.

Coupled inceptors including manual and automatic decoupling functions were tested under the same conditions. The results of this thesis indicate that the takeover maneuvers in low level flight through both inceptor decoupling methods were performed without overcontrol. The possibility to decouple controls not only reduced the amplitude of the control used in the tasks, but also alleviated the control activity. When the decoupling was present, the pilots used a control strategy that enables faster stabilization of the helicopter compared to the option without decoupling.

Pilots considered the priority (decoupling) functions reliable, predictable and easy. Consequently, experimental pilots successfully performed the takeover control maneuver with lower levels of perceived workload. The priority functions mean values showed workload reduction of 29% (automatic inceptor decoupling) and 34% (manual inceptor decoupling) in comparison with a configuration without inceptor decoupling. The decoupling functions were well accepted by the experimental pilots. Positive ratings in usefulness and satisfying scales were assigned. The priority configurations (both automatic and manual inceptor decoupling) were considered useful and achieved positive satisfaction level.

Due to the flexibility and superior performance of the decoupling methods against the design without decoupling means, a variable inceptor coupling configuration that includes decoupling functions was considered validated to assist pilots during takeover control in low level flight.

9.1 Answer of the Scientific Questioning

Returning to the scientific questioning posed at the beginning of this thesis, it is now possible to answer it due to the previously mentioned findings.

Scientific Questioning: *how can electronically coupled active sidesticks assist the flight instructor to takeover control in dual pilot helicopters?*

Answer: This work has identified two essential characteristics of the electronically coupled active sidesticks to effectively assist the flight instructor to takeover control in dual pilot helicopters. Firstly, in the coupled inceptors, the force feedback of the system pilot can provide cues to increase the situational awareness of the flight instructor/ pilot monitoring. Secondly, the decoupling methods can increase the pilot authority and assist pilots in takeover control maneuvers. The decoupling methods depended on the implementation of a variable inceptor coupling system in active sidesticks for helicopters, which was validated by this thesis. This system proved the ability of the active sidesticks to support the flight instructor/ pilot monitoring to takeover control in low level flight, due to the reduction of force fight time and substantial decreasing of attitude oscillation. To attain such result, this research proposed a method to mitigate the oscillations during takeover control by reducing the control activity through adaptive fading of the opposing force.

The overall results improve the understanding of the novel decoupling functions for dual pilot helicopters. Due to safety significance of these functions for future FCS, these demonstrations provide compelling evidence that at least one decoupling function shall be implemented in the upcoming active coupled inceptors.

9.2 Considerations for Future Work

Further studies need to be carried out to validate the variable inceptor coupling in other scenarios. It should be emphasized that the activation of the automatic decoupling requires the definition of which control cabin will be deactivated and which one will be prioritized. Test and training flights imply the designation of safety pilot and instructor pilot, respectively, therefore the indication of the control cabin to be prioritized is straightforward. The same reasoning cannot be applied to all types of flight. Therefore, future work might concentrate effort in defining the application of the automatic decoupling function to different scenarios.

Further research is recommended to assess the effects of the inceptor decoupling functions in other cases of control interference, such as inceptor jam and sidestick malfunction. Supplementary research is currently being carried out to explore handling deficiencies during active control inceptor failures situations [173]. In such situations, the ability for electronic decoupling may allow for the continued safe flight of the vehicle. Moreover, a fruitful area for further work is the analysis of the force fading logic to alleviate PIO effects.

The present thesis focused on the automatic decoupling via cyclic force threshold, since it was considered the most challenging and critical condition. Future research should therefore concentrate on the investigation of the impact on the controllability of collective and pedal decoupling.

The main limitation lies in the fact that the number of pilots that participated in the experiments restricted the confidence level to 95%. Therefore, to increase the confidence level, a large number of subjects is recommended.

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Appendix A Handling Qualities Evaluation

This appendix presents the plots and results of the measured simulation data against the ADS-33E-PRF predicted criteria in hover condition [114]. The basic helicopter model is analyzed in section A.2 and the degraded stability helicopter model in section A.3. Initially, section A.1 provides the basis for understanding the requirements through the criteria description.

A.1 ADS-33E-PRF Predicted Criteria Description

The description of the ADS-33E-PRF criteria is based on the academic work in [153], which correlates the standard guidelines to the practical experience of the United States Naval Test Pilot School.

Bandwidth. The bandwidth frequency correlates to the highest frequency at which the pilot can make control inputs and still be able to correctly predict the aircraft response. Inputs at frequencies higher than the bandwidth frequency will result in aircraft motion with different magnitude and phase delay than the lower frequencies, and the combination of this change and the increasing phase delay makes pilot prediction of aircraft response more difficult and increases the probability of Pilot-Induced Oscillations (PIO).

Dynamic Stability. The motion that results once the aircraft has been disturbed from steady-state conditions is the focus of the dynamic stability requirement, also known as mid-term response to control inputs. This portion of the small-amplitude attitude change requirement addresses the requirement for the pilot to focus on tasks other than controlling the aircraft for short periods without the aircraft making significant excursions from its flight path. The natural frequency of the aircraft and the damping ratio for the resulting oscillations are the critical parameters for the mid-term response requirement. The dynamic stability criterion is applicable at all frequencies below the bandwidth frequency, and thus addresses the lower frequency modes of phugoid and Dutch-roll.

Attitude Quickness. The requirement for moderate amplitude attitude changes is also-called attitude quickness by ADS-33. The requirements call for a specific ratio of the maximum rate of change of the attitude parameter in question to the value of the change in attitude achieved. The criterion shows how fast the helicopter is able to transition from one stationary attitude to another stationary attitude without large pilot corrections. It is a measure of agility, or the quickness and accuracy in moving from one attitude to another in flight.

Inter-Axis Coupling (pitch-roll and yaw-collective). ADS-33 includes limits on the maximum amounts of inter-axis coupling allowed for each handling quality Level. The basic ADS-33 test for inter-axis coupling is to make a single-axis step input to the flight controls, while holding the other control axes fixed. The ratio of the off-axis response to the response in the axis of control input is then measured by comparing the rates of change in aircraft attitude at a specific time after the control input, usually 4 seconds. ADS-33 limits the ratio of off-axis to primary axis response to be less than specified amounts based on the axes in question.

Height Response. ADS-33 requires that the vertical rate response of the aircraft to a step input on the collective shall have "a qualitative first-order appearance for at least 5 seconds" (ADS-33D, 1994). ADS-33 also sets limits on how long the vertical rate response takes to get to a steady-state value following a collective step input and requires a minimum achievable vertical rate 1.5 seconds after the collective step input. The response to the collective controller is measured in the time domain since issues of torque control, engine management, and rotor RPM governing all have significant impacts on the handling qualities of the vertical axis. Hoh *et al.* [174] found that "a time domain equivalent systems approach was found to be the best compromise for describing and specifying the vertical rate response".

Torque. Torque, or any other parameter displayed to the pilot as a measure of the maximum allowable power that can be commanded without exceeding engine or transmission limits, shall have dynamic response characteristics that fall within the limits specified by the ADS-33. This requirement shall apply if the displayed parameter must be manually controlled by the pilot to avoid exceeding displayed limits.

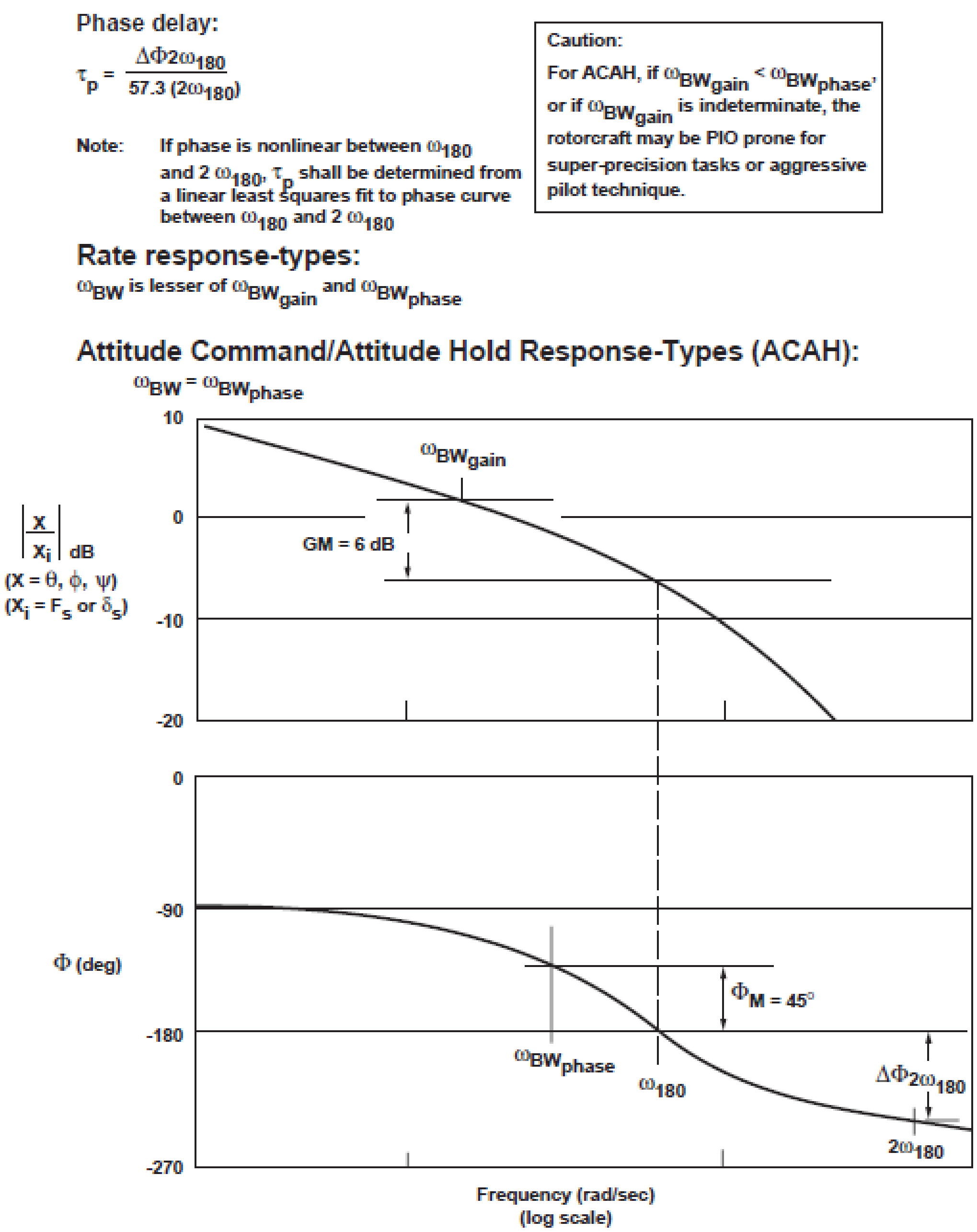

Figure A.1: Criterion of bandwidth and phase delay [114]

A.2 Predicted Criteria Results (Baseline Helicopter)

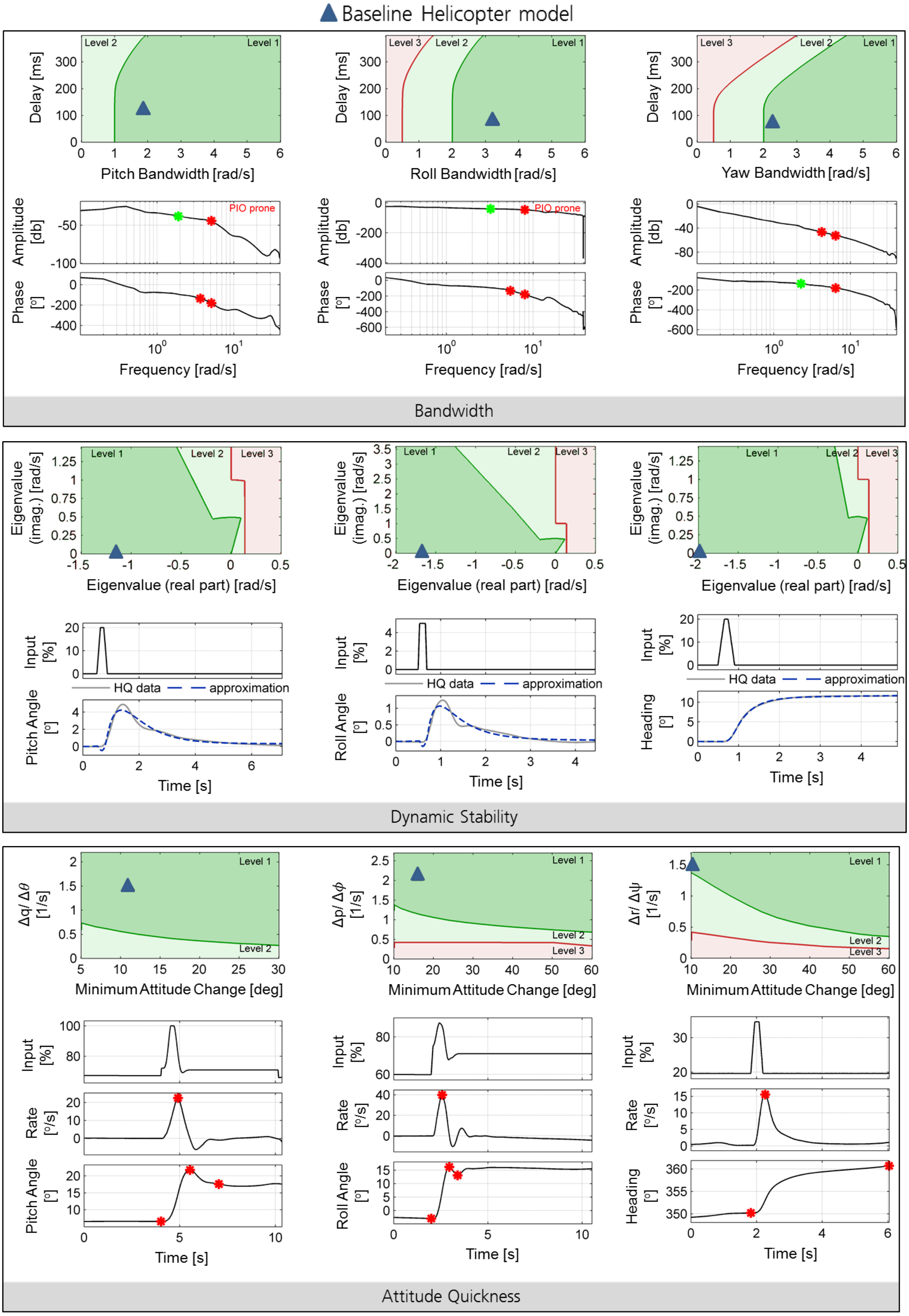

Figure A.2: Bandwidth, dynamic stability and attitude quickness criteria

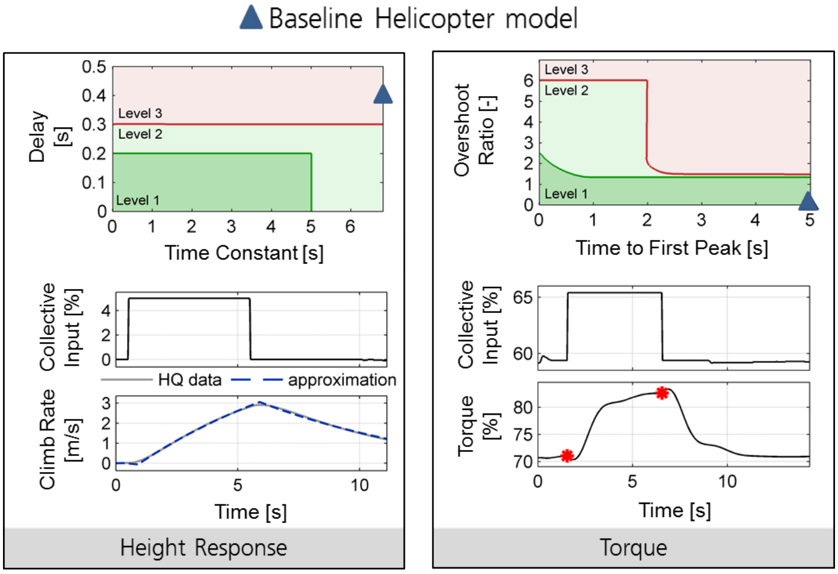

Figure A.3: Height response and torque criteria

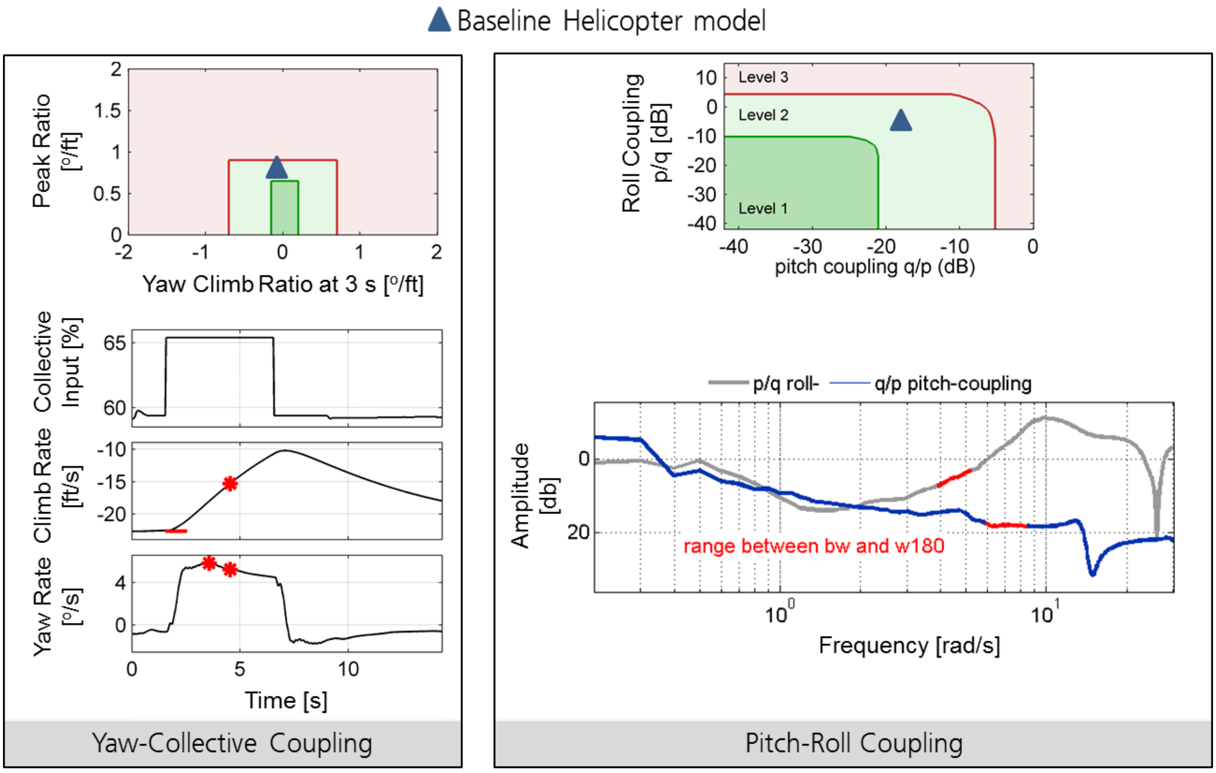

Figure A.4: Yaw-collective coupling and pitch-roll coupling criteria

Table A.1: Inputs for HQ predicted criteria analysis (baseline helicopter model)

Criterion	Speed	Input Axis	Input Type
Bandwidth	0	Longitudinal	Sweep
	0	Lateral	Sweep
	0	Yaw	Sweep
Dynamic Stability	0	Longitudinal	Step/impulse
	0	Lateral	Step/impulse
	0	Yaw	Step/impulse
Attitude Quickness	0	Longitudinal	Quick input
	0	Lateral	Quick input
	0	Yaw	Quick input
Height Response	0	Heave	Step
Torque	0	Heave	Step
Coupling Pitch-Roll	0	Longitudinal and lateral	Sweep
Coupling Collective-Yaw	0	Heave	Step

Table A.2: Results of the HQ predicted criteria analysis (baseline helicopter model)

Criterion	Input Axis	X-Axis		Y-Axis	
		Value	Unit	Value	Unit
Bandwidth	Longitudinal	1.89	[rad/s]	0.12	[ms]
	Lateral	3.25	[rad/s]	0.08	[ms]
	Yaw	2.27	[rad/s]	0.07	[ms]
Dynamic Stability	Longitudinal	-1.18	[rad/s]	0.00	[rad/s]
	Lateral	-1.66	[rad/s]	0.00	[rad/s]
	Yaw	-1.97	[rad/s]	0.00	[rad/s]
Attitude Quickness	Longitudinal	11.04	[deg]	1.48	[1/s]
	Lateral	16.10	[deg]	2.08	[1/s]
	Yaw	10.55	[deg]	1.47	[1/s]
Height Response	Heave	8.73	[s]	0.39	[s]
Torque	Heave	5.01	[s]	0.00	[-]
Coupling Pitch-Roll	Longitudinal and lateral	-17.81	[dB]	-5.72	[dB]
Coupling Collective-Yaw	Heave	-0.08	[°/ft]	0.79	[°/ft]

A.3 Predicted Criteria Results (Modified Helicopter)

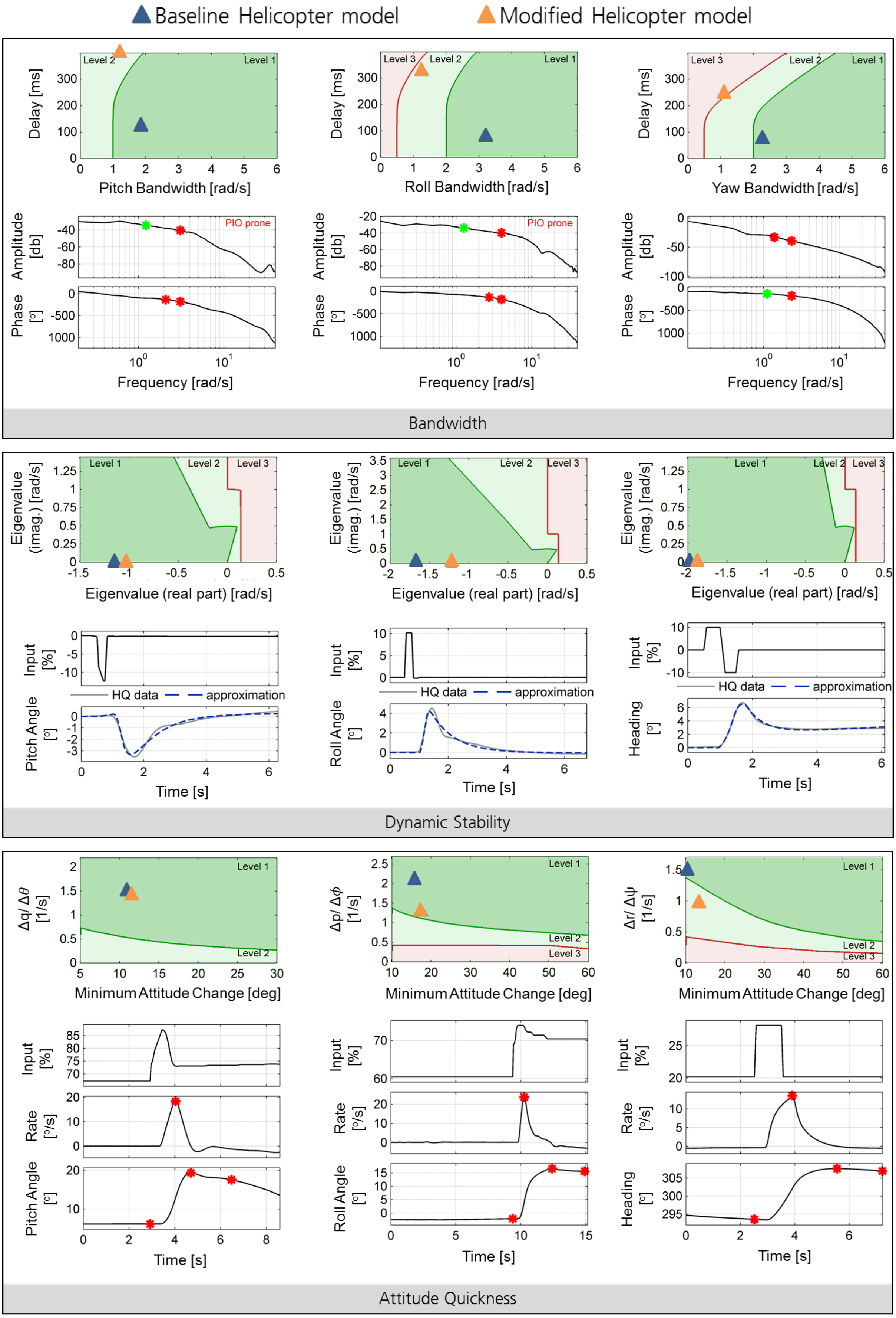

Figure A.5: Bandwidth, dynamic stability and attitude quickness criteria

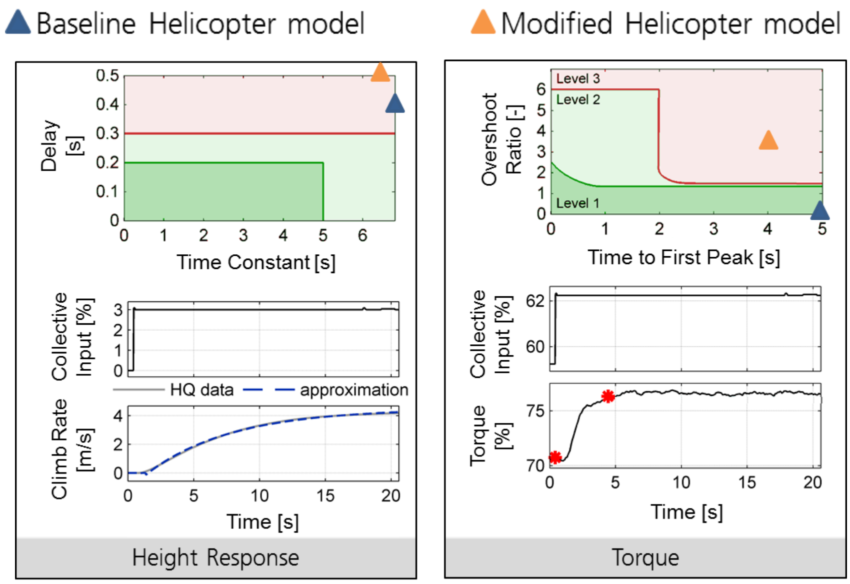

Figure A.6: Height response and torque criteria

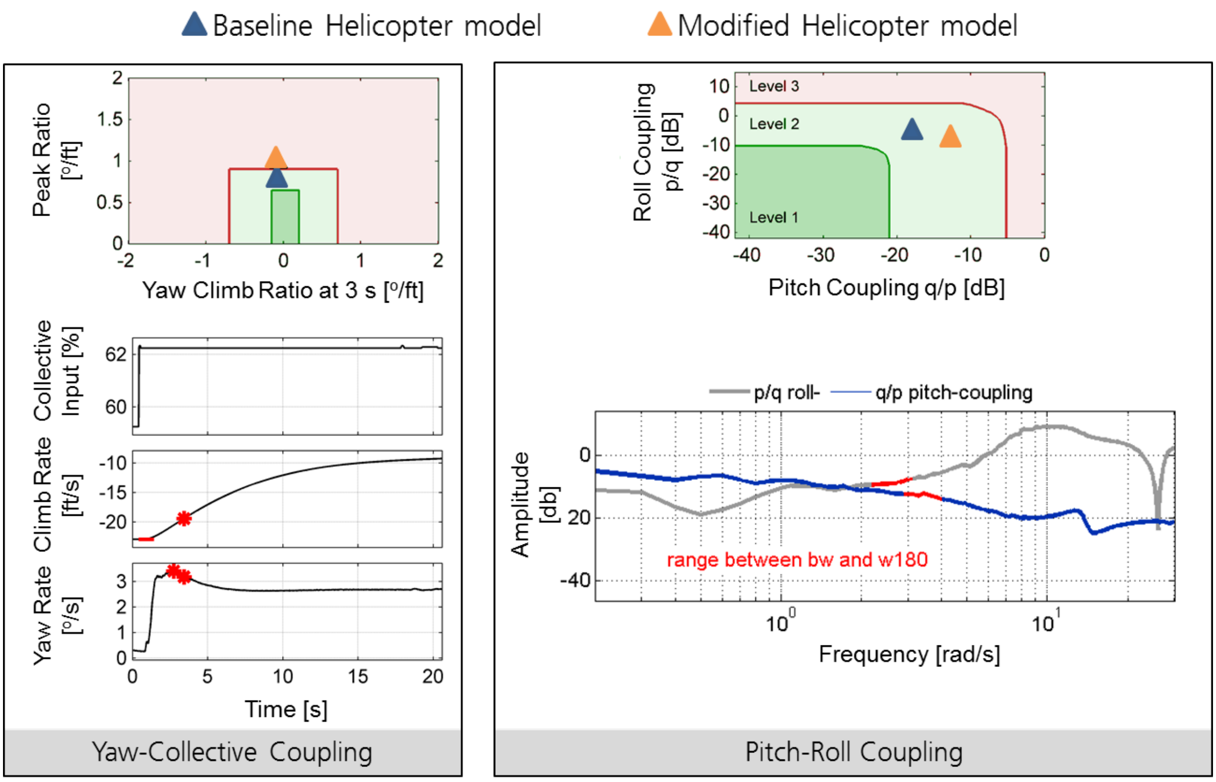

Figure A.7: Yaw-collective coupling and pitch-roll coupling criteria

Table A.3: Inputs for HQ predicted criteria analysis (modified helicopter model)

Criterion	Speed	Input Axis	Input Type
Bandwidth	0	Longitudinal	Sweep
	0	Lateral	Sweep
	0	Yaw	Sweep
Dynamic Stability	0	Longitudinal	Step/impulse
	0	Lateral	Step/impulse
	0	Yaw	Doublet
Attitude Quickness	0	Longitudinal	Quick input
	0	Lateral	Quick input
	0	Yaw	Quick input
Height Response	0	Heave	Step
Torque	0	Heave	Step
Coupling Pitch-Roll	0	Longitudinal and lateral	Sweep
Coupling Collective-Yaw	0	Heave	Step

Table A.4: Results of the HQ predicted criteria analysis (modified helicopter model)

Criterion	Input Axis	X-Axis		Y-Axis	
		Value	Unit	Value	Unit
Bandwidth	Longitudinal	1.23	[rad/s]	0.44	[ms]
	Lateral	1.27	[rad/s]	0.33	[ms]
	Yaw	1.11	[rad/s]	0.24	[ms]
Dynamic Stability	Longitudinal	-1.02	[rad/s]	0.00	[rad/s]
	Lateral	-1.21	[rad/s]	0.00	[rad/s]
	Yaw	-1.88	[rad/s]	0.00	[rad/s]
Attitude Quickness	Longitudinal	11.45	[deg]	1.38	[1/s]
	Lateral	17.75	[deg]	1.26	[1/s]
	Yaw	13.44	[deg]	0.96	[1/s]
Height Response	Heave	6.45	[s]	0.92	[s]
Torque	Heave	4.01	[s]	3.48	[-]
Coupling Pitch-Roll	Longitudinal and lateral	-12.77	[dB]	-8.79	[dB]
Coupling Collective-Yaw	Heave	-0.06	[°/ft]	0.97	[°/ft]

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Appendix B Mission Task Elements

This appendix presents the descriptions of the mission task elements (MTEs), which were developed based on the structure of the ADS-33E [114]. The tasks were adapted to this thesis, because the mentioned standard does not address dual pilot operation. The following MTEs are specified in this appendix:

B.1 Transverse reposition
B.2 Transition to hover
B.3 Approach to helipad
B.4 Vertical departure
B.5 Hover in confined area

The MTE is a term originated from the breakdown of a complete mission into elements, which represent critical tasks [175]. Typically, a MTE is a maneuver that requires good handling qualities. Although the resulting task is not representative of a normal operational activity, the MTE intends to expose problems in precision maneuvers that might be important in specific circumstances [175].

The indication of the level of flying qualities via assigned Cooper-Harper HQRs [139] is required only in the transition to hover MTE. Thus, the description of this maneuver provides both desired and adequate performance, including the same performance boundaries as the ones specified in hover MTE from ADS 33E for cargo/utility helicopter in good visual environment [114]. The other four MTE of this thesis are demonstration maneuvers (without HQRs) including only the desired performance limits, which provides substantial details to ensure that all pilots perform nearly the same way. It is also useful to the instructor pilot, in order to identify a condition which the trainee pilot is flying out of the proposed task limits.

The initial conditions of the tests were set as following: 2600 kg takeoff weight, visual meteorological conditions, Manching airfield, 1013.25 hPa atmospheric pressure at sea-level, calm wind, 26.9°C, and density of 1.115 kg/m^3.

B.1 Transverse Reposition MTE

Objective of the maneuver

- Check usefulness of the follow through technique to monitor sidestick inputs of the other pilot
- Compare the contribution of coupled and uncoupled cross-cockpit inceptors for situation awareness
- Check for objectionable transients in take overcontrol maneuvers without inceptor decoupling

Description of the maneuver. The trainee pilot initially flies the helicopter in a stabilized hover with the longitudinal axis of the rotorcraft oriented approximately 45° to the reference line marked on the ground. The experimental pilot acts as the flight instructor. The trainee initiates the maneuver at a ground speed of between 10 kt and 20 kt (target speed 15 kt), at an altitude between 40 ft and 60 ft (target height 50 ft). In order to monitor the trainee inputs, the flight instructor uses the follow through technique (guard inceptors closely). The flight instructor helps the trainee pilot by interfering in flight control if the flight performance is out of the tolerance limits. The interferences can be partial (helping in one axis) or full (taking over controls). Repeat the maneuver in the opposite direction.

Description of the test course. The suggested test course for this maneuver is shown in Figure B.1. The test path consists on the reference line indicating the desired track. Any feature of the scenario can be considered as an obstacle (i.e., building, trees, traffic lights, etc.). The final point of the maneuver is the X point before the power line.

Performance standards. The flight instructor should monitor the performance of the trainee pilot according to the performance described in Table B.1.

Table B.1: Performance standards for the transverse reposition MTE

Performance	Desired	Tolerance
Maintain minimum longitudinal and lateral distance of any obstacle	20 ft	10 ft
Maintain height	50 ft	±10 ft
Maintain heading	230° or 050°	±10°
Maintain speed	15 kt	±5 kt

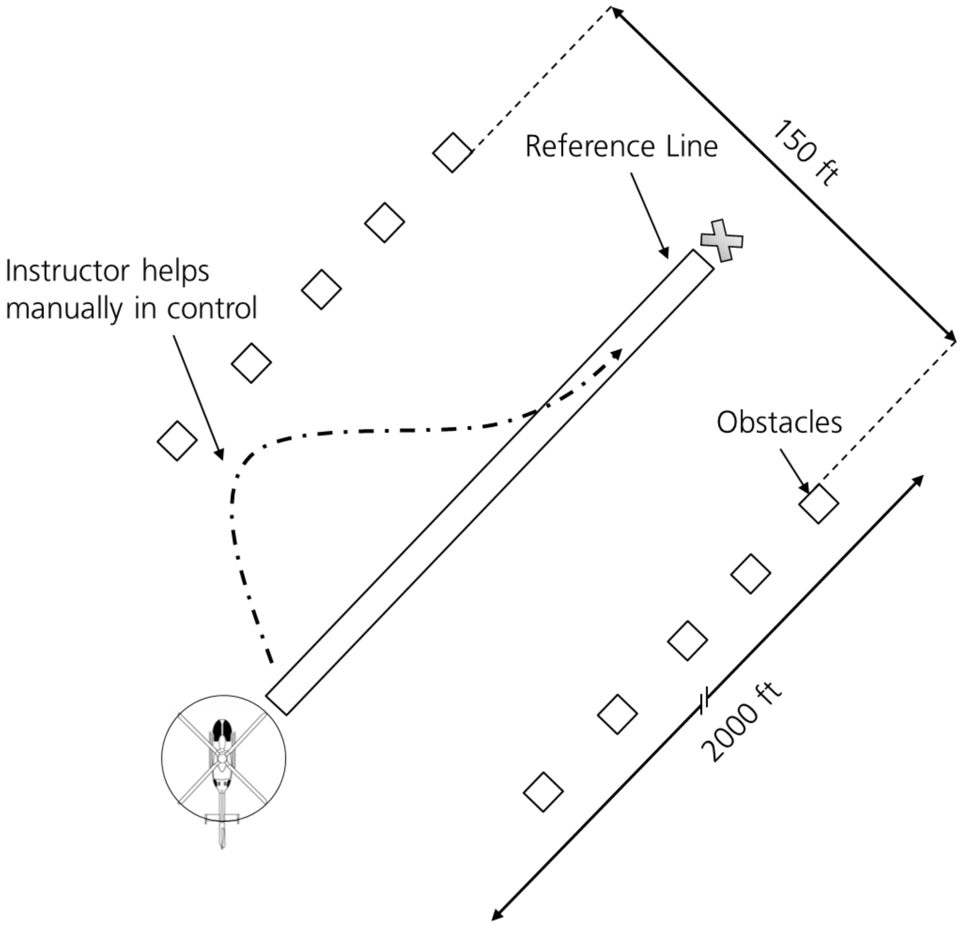

Figure B.1: Test course for transverse reposition MTE

B.2 Transition to Hover MTE

Objective of the maneuver

- Check ability for pilot override during translating flight
- Check ability to perform a stabilized hover with precision and a reasonable amount of aggressiveness after an automatic inceptor decoupling
- Check for objectionable transients in takeover control maneuvers (with inceptor decoupling)

Description of the maneuver. The trainee pilot initiates the maneuver at a ground speed of between 6 and 10 knots, at an altitude less than 20 ft. The target hover point shall be oriented approximately 45° relative to the heading of the rotorcraft. The experimental pilot acts as the flight instructor. In order to monitor the trainee inputs, the flight instructor uses the follow through technique (guard inceptors closely). The flight instructor shall counteract the trainee pilot in case of inappropriate input regarding the ground track. When the automatic inceptor decoupling is activated, the flight instructor shall takeover control and complete the transition to hover. The target hover point is a repeatable, ground-referenced point from which rotorcraft deviations are measured. The ground track should be such that the rotorcraft will arrive over the target hover point.

Description of the test course. The suggested test course for this maneuver is shown in Figure B.2. Note that the hover altitude depends on the height of the hover sight and the distance between the sight, the hover target, and the rotorcraft. These dimensions may be adjusted to achieve a desired hover altitude.

Performance standards. Accomplish the transition to hover in one smooth maneuver. It is not acceptable to accomplish most of the deceleration well before the hover point and then to creep up to the final position. Table B.2 contains the detailed performance standards.

Table B.2: Performance standards for the transition to hover MTE

Performance	Desired	Adequate
Attain a stabilized hover within X s of initiation of deceleration	5 s	8 s
Maintain a stabilized hover for at least	30 s	30 s
Maintain the longitudinal and lateral position within ±X ft of a point on the ground	3 ft	6 ft
Maintain altitude within ±X ft	2 ft	4 ft
Maintain heading within ±X°	5°	10°
There shall be no objectionable oscillations in any axis either during the transition to hover or the stabilized hover	✓	Not applicable

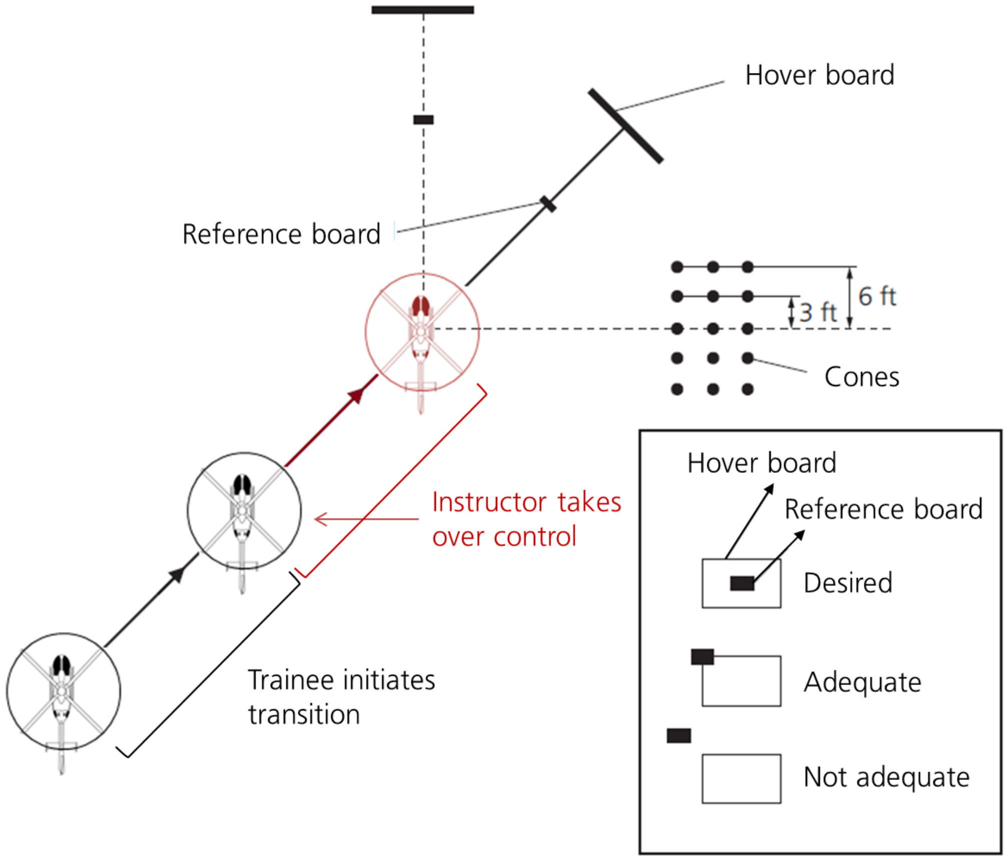

Figure B.2: Test course for transition to hover MTE

B.3 Approach to Helipad MTE

Objective of the maneuver

- Check ability to precisely takeover control with and without inceptor decoupling
- Check ability to perform transition to hover after overriding the pilot flying
- Check ability to recognize the inceptor decoupling through tactile, visual or aural warning
- Check for objectionable transients in takeover control maneuvers

Description of the maneuver. The trainee pilot initially flies the helicopter in final approach to helipad at 300 ft and 60 kt. The experimental pilot acts as the flight instructor. The trainee pilot performs a normal manual deceleration until 60 ft AGL. At this point, an inappropriate pitch up attitude (+12°) without collective compensation causes fast deceleration and increased rate of descend, so the helicopter moves toward a preceding area relative to the helipad. The flight instructor shall interfere on control to correct the helicopter trajectory by overriding the trainee pilot, if s/he judges the need to takeover control. Subsequently the interference, the trainee pilot relinquishes inceptors after 1.5 seconds (±0.5 seconds tolerance) or after a decoupling. The maneuver is complete when a stabilized hover at the helipad is achieved.

Description of the test course. The suggested trajectory for this maneuver is shown in Figure B.3. The helipad must be clearly marked out on the ground.

Performance standards. Table B.3 contains the detailed performance standards.

Table B.3: Performance standards for the approach to helipad MTE

Performance	Desired	Tolerance
Maintain minimum longitudinal and lateral distance of any obstacle	15 ft	±5 ft
Maintain height AGL (hover)	15 ft	±5 ft
Maintain heading	180°	±10°
Maintain a stabilized hover for at least	10 s	Not applicable
Minimum helicopter speed (trainee pilot, before inappropriate input)	15 kt	±5 kt

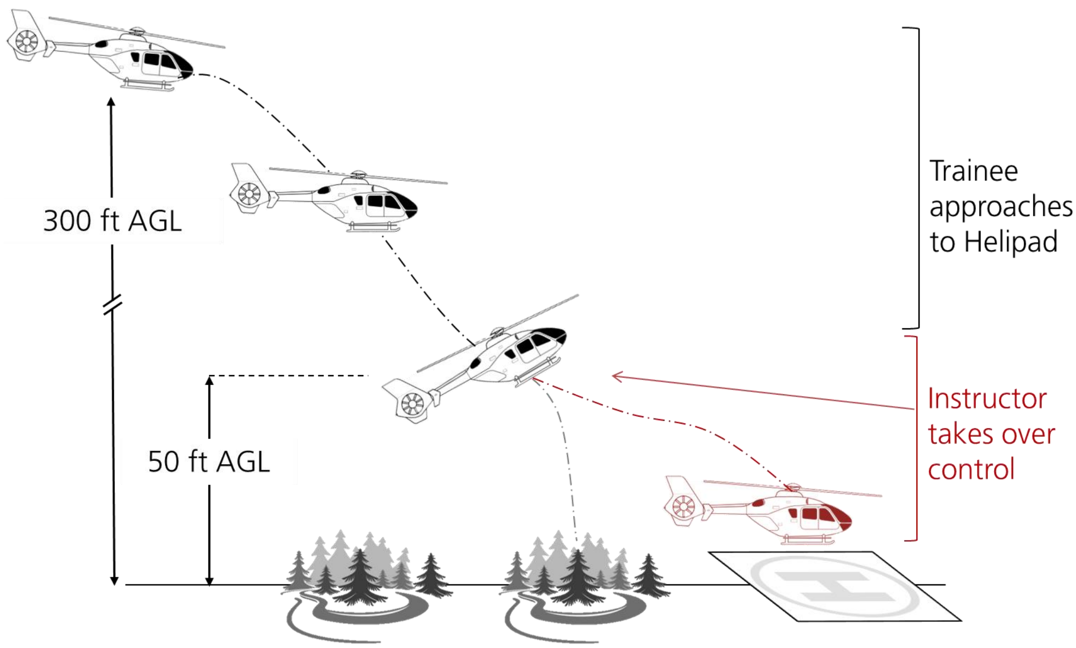

Figure B.3: Test course for approach to helipad MTE

B.4 Vertical Departure MTE

Objective of the maneuver

- Check ability to precisely takeover control with and without inceptor decoupling
- Check ability to perform vertical departure after overriding the pilot flying
- Check ability to recognize the inceptor decoupling through tactile, visual or aural warning
- Check for objectionable transients in takeover control maneuvers

Description of the maneuver. The trainee pilot initially flies the helicopter in stabilized hover over the helipad at 15 ft. The experimental pilot acts as the flight instructor. The trainee pilot performs a vertical departure until 150 ft AGL due to the obstacle height. Between 50 ft and 100 ft, the helicopter drifts laterally towards the obstacles near the helipad as the consequence of inappropriate lateral inputs. The flight instructor shall correct the helicopter trajectory by overriding the trainee pilot, if s/he judges the need to takeover control. Subsequently the interference, the trainee pilot relinquishes inceptors after 1.5 seconds (±0.5 seconds tolerance) or after a decoupling. The maneuver is complete when a stabilized hover at 150ft is achieved. Repeat the maneuver to the obstacles at the other side (left/right).

Description of the test course. The suggested trajectory for this maneuver is shown in Figure B.4. The obstacles consist of electricity transmission towers at 120 ft.

Performance standards. Table B.4 contains the detailed performance standards.

Table B.4: Performance standards for the vertical departure MTE

Performance	Desired	Tolerance
Maintain minimum longitudinal and lateral distance of any obstacle	15 ft	±5 ft
Maintain speed	0 kt	±5 kt
Maintain height AGL (hover)	150 ft	±10 ft
Maintain heading	180° or 360°	±10°

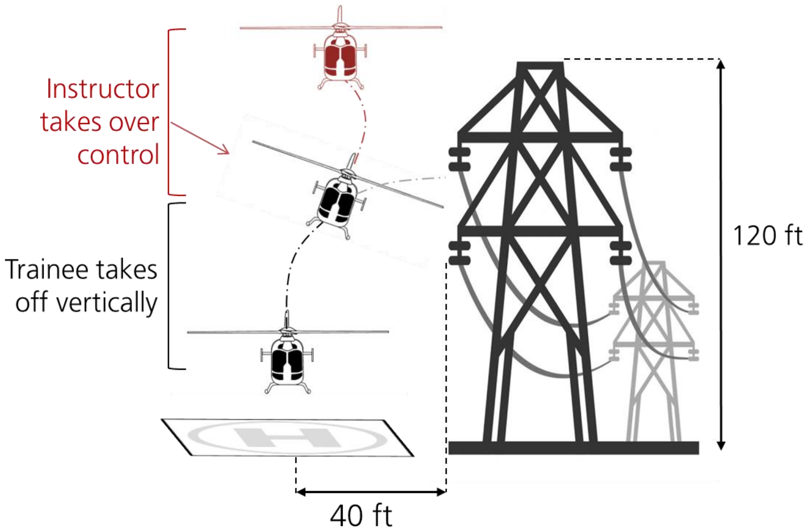

Figure B.4: Test course for vertical departure MTE

B.5 Hover in Confined Area MTE

Objective of the maneuver

- Check ability to precisely takeover control with and without inceptor decoupling
- Check ability to perform hover after overriding the pilot flying in confined area
- Check ability to recognize the inceptor decoupling through tactile, visual or aural warning
- Check for objectionable transients in takeover control maneuvers

Description of the maneuver. The trainee pilot initially flies the helicopter in stabilized hover inside a confined area at 15 ft. The experimental pilot acts as the flight instructor. The trainee pilot gradually increases the oscillation simulating a PIO (pilot induced oscillations) in roll axis. The flight instructor shall maintain minimum obstacle clearance of 10 ft and avoid excessive acceleration towards the surround trees. The flight instructor overpowers the trainee pilot, if the takeover control is judged necessary. Subsequently the interference, the trainee pilot relinquishes inceptors after 1.5 seconds (±0.5 seconds tolerance) or after a decoupling. The maneuver is complete when a stabilized hover inside the confined area is achieved by the flight instructor.

Description of the test course. The suggested dimensions of the confined area are shown in Figure B.5. The obstacles consist of trees.

Performance standards. Table B.5 contains the detailed performance standards.

Table B.5: Performance standards for the vertical departure MTE

Performance	Desired	Tolerance
Maintain minimum longitudinal and lateral distance of any obstacle	15 ft	±5 ft
Maintain speed	0 kt	±5 kt
Maintain height AGL (hover)	15 ft	±10 ft
Maintain heading	180°	±10°

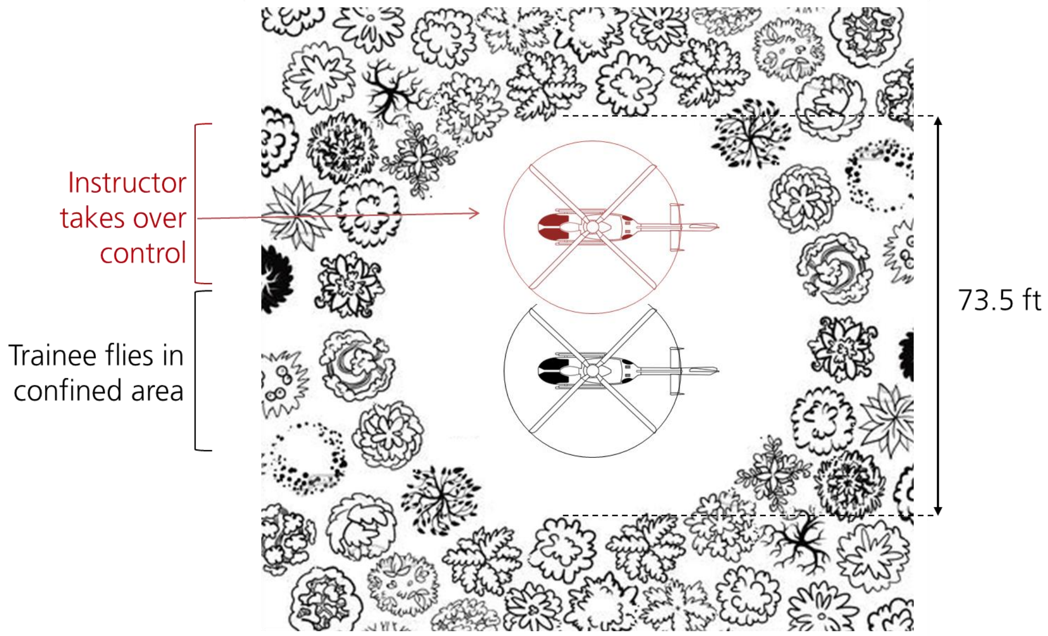

Figure B.5: Test course for vertical departure MTE

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Appendix C Pilots' Experience

This appendix presents the background of the pilots who participated in the three main evaluations, which are:

C.1 Situation awareness test (3 test pilots)

C.2 Force threshold assessment (4 test pilots)

C.3 System validation: pilot workload and pilot acceptance (3 test pilots and 2 operational pilots)

Altogether, twelve subjects took part in the three main evaluations.

Three pilots participated in two evaluations; therefore, nine different pilots were involved in total (namely pilots A to I).

C.1 Situation Awareness Test

Three pilots participated in the situation awareness test, as shown in Table C.1.

Table C.1: Pilots' background of the situation awareness test

Topic	Test Pilots		
	Pilot A	Pilot B	Pilot C
Age [years]	44	60	37
Gender	Male	Male	Male
Test Pilot	Yes	Yes	Yes
Flight experience [hours]	4000	6300	1800
Main helicopters	EC-135 BO-105 AS-350 A-109 SH-3 CH-47 SA-342 WG-13 Bell 412	EC-135 BO-105 SA-318 Bell 412 Bell 205	EC-135 AS-350 AS-355 AS-365 Mi-35M AS-332 UH-60 Bell 206
Main missions	Test flight, training, attack, combat, transport, search and rescue	Test flight, training, attack, combat, VIP, utility, search and rescue	Test flight, training, attack, combat, VIP, transport, utility, search and rescue
Sidestick experience	Yes (ACT/FHS)	Yes (ACT/FHS)	Yes (AVES simulator)
Flight instructor	Yes	Yes	Yes
Flight instruction helicopter	SH-3 A-109 SA-342	BO-105 EC-135	AS-350 AS-355 UH-60

C.2 Force Threshold Assessment

Four pilots participated in the force threshold assessment, as shown in Table C.2.

Table C.2: Pilots' background of the force threshold assessment

Topic	Test Pilots			
	Pilot C	Pilot D	Pilot E	Pilot F
Age [years]	37	40	59	46
Gender	Male	Male	Male	Male
Test Pilot	Yes	Yes	Yes	Yes
Flight experience [hours]	1800	2300	5000	4200
Main helicopters	EC-135 AS-350 AS-355 AS-365 Mi-35M AS-332 UH-60 Bell 206	BO-105 AS-355 NH-90 CH-53 A-109 UH-1D SA-318 S-55 MD-500 H-300 Bell 206	BO-105 NH-90 CH-53 UH-1D/H SH-3 SA-342 H-300 WG-13	BO-105 H-145 UH-Tiger CH-53 UH-1D/H
Main missions	Test flight, training, attack, combat, VIP, transport, utility, search and rescue	Test flight, training, utility, aerial work	Test flight, training, attack, combat, utility, search and rescue	Test flight, training, attack, combat, transport, utility
Sidestick experience (project)	Yes (AVES simulator)	Yes (NRC helicopter)	No	Yes (NRC B206, CH53K simulator, ACT/FHS)
Flight instructor	Yes	Yes	Yes	Yes
Flight instruction helicopter	AS-350 AS-355 UH-60	NH-90 CH-53 UH-1D	NH-90 UH-1D/H WG-13	CH-53 UH-1D/H UH-Tiger H-145

C.3 System Validation: Pilot Workload and Pilot Acceptance

Five pilots participated in the system validation, which includes the investigation of pilot workload and pilot acceptance, as shown in Table C.3.

Table C.3: Pilots' background of the system validation

Topic	Pilots				
	Pilot A	Pilot B	Pilot G	Pilot H	Pilot I
Age [years]	44	60	53	45	40
Gender	Male	Male	Male	Male	Male
Test Pilot	Yes	Yes	No	Yes	No
Flight experience [hours]	4000	6300	5000	3700	800
Main helicopters	EC-135 BO-105 AS-350 A-109 SH-3 CH-47 SA-342 WG-13 Bell 412	EC-135 BO-105 SA-318 Bell 412 Bell 205	BO-105 SA-318 UH-1D CH-53G Bell 206	SA-341/342 AS-355 SA-330 AS-332M EC-725 WG-13 NH-90 A-109 AS-350 Tiger	EC-135 BO-105 UH-1D CH-53G Cabri-G2
Main missions	Test flight, training, attack, combat, transport, search and rescue	Test flight, training, attack, combat, VIP, utility, search and rescue	Training, VIP, transport, utility, search and rescue	Test flight, training, utility, search and rescue	Training, transport, utility
Sidestick experience (project)	Yes (ACT/FHS)	Yes (ACT/FHS)	No	Yes (NRC helicopter, AH-1Z Viper, AVES simulator)	Yes (ACT/FHS)
Flight instructor	Yes	Yes	Yes	Yes	No
Flight instruction helicopter	SH-3 A-109 SA-342	BO-105 EC-135	CH-53G	NH-90 AS-332M AS-330	-

Appendix D Questionnaires and Scales

This appendix presents the questionnaires and scales used throughout this work. These are:

D.1 Situational Awareness Global Assessment Technique (SAGAT)
D.2 Transient Rating Scale
D.3 Integrated Transient Classification
D.4 Cooper-Harper Rating Scale
D.5 PIO Rating Scale
D.6 NASA Task Load Index
D.7 Acceptance Scale
D.8 Interview

D.1 SAGAT Survey

D.1.1 Briefing

Aim of the study. The research targets the investigation of electronic coupling to emulate the mechanical linkage between control stations. The purpose of this study is to assess the SA of pilots in cabin featuring electronic couple active sidesticks through the method of SAGAT.

Anonymity and Voluntary answers. Participation in this survey is voluntary. The data are analyzed anonymously and are used exclusively for the assessment of proposed systems.

Definitions.

- SA. It is formally defined as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future" [73].
- SA Levels. SA involves perceiving critical factors in the environment (Level 1 SA), understanding what those factors mean, particularly when integrated together in relation to the aircrew's goals (Level 2), and at the highest level, an understanding of what will happen with the system in the near future (Level 3). These higher levels of SA allow pilots to function in a timely and effective manner [80].
- SAGAT. It is an objective measure of SA. SAGAT employs periodic, randomly-timed freezes in a simulation scenario during which all of the operator's displays are temporarily blanked. At the time of the freeze a series of queries are provided to the operator to assess his or her knowledge of what was happening at the time of the freeze. The queries typically cover SA elements at all three levels of SA (perception, comprehension and projection) [132].

Procedures. Training trials will be conduct in which the simulator is halted frequently. A questionnaire type containing a portion of SAGAT queries is randomly selected and asked each time, when experimental pilots (EPs acting as flight instructor) shall answer the queries. No display or other visual aids shall be visible while answering the queries. If EPs do not know or are uncertain about the answer to a given query, they should be encouraged to make their best guess. There is no penalty for guessing (it derives from experience and is part of the embedded schema in decision making). If EPs do not feel comfortable enough to make a guess, they may go on to the next question. Due to the attentional narrowing or lack of information, certain questions may seem unimportant to a pilot at the time of a given stop. EPs should attempt to answer the queries anyway.

D.1.2 SA Cognitive Task Analysis

In the cognitive task analysis, the major goals for the task are identified, along with the major subgoals necessary for meeting each of these goals. Associate with each subgoal, the major decisions that need to be made are then pointed out [176]. The goal-directed task analysis for the SAGAT Survey is described in the Table D.1.

Table D.1: Goal-directed task analysis

Task	Goals	Sub goals	Decisions	Level 1 SA	Level 2 SA	Level 3 SA
Flight instruction	Trainee pilot learning	Monitor performance	Suggest adjustments	Input: axis direction	-	Future control correction
	Safety: avoid accident	Clearance to obstacles	Control intervention	Nearest obstacle	Control strategy vs. obstacle	Most unsafe obstacle
Task performance	Speed maintenance	Speed tolerance	Correct inputs accordingly or suggest adjustments	Speed condition	Task: speed tolerance	Next speed variation
	Heading maintenance	Heading tolerance		Heading condition	Task: heading tolerance	Next heading variation
	Height maintenance	Height tolerance		Height condition	Task: height tolerance	Next height variation
Secondary Task	Identify lights on	Read and mark	Timely touch the screen	Last light on	Task: number of lights on	-

D.1.3 SAGAT Query list

Based on the goal-directed task analysis, the SAGAT queries are listed below. The fifteen questions are divided in six questionnaire types.

Table D.2: SAGAT query list

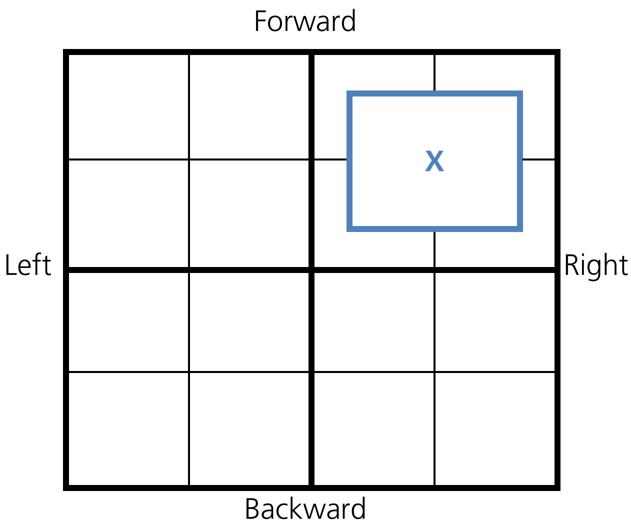
SA Level	Number #	Description	Questionnaire type
1	1.1	Enter the axis/direction of the trainee pilot input (last 3 s).	I, V
	1.2	Enter the helicopter current position.	III
	1.3	Enter the speed of the helicopter.	II, VI
	1.4	Enter the heading of the helicopter.	IV
	1.5	Enter the height of the helicopter.	IV
	1.6	Enter the last light that turned on.	I, V
2	2.1	Enter the nearest/ most critical obstacle (last 3 s).	IV
	2.2	Enter the number of times that the helicopter has flown out of the speed tolerance.	III
	2.3	Enter the number of times that the helicopter has flown out of the heading tolerance.	I, V
	2.4	Enter the number of times that the helicopter has flown out of the height tolerance.	II
	2.5	Enter the total number of lights on.	II, VI
3	3.1	Enter the recommended control input to maintain the helicopter within the tolerance performance.	III, IV
	3.2	In the next 5 s, which variation in speed do you expect?	I, V
	3.3	In the next 5 s, which variation in height do you expect?	III
	3.4	In the next 5 s, what is the future position of the helicopter?	II, VI

D.1.4 SAGAT Questionnaire Types

The queries are numbered based on the questionnaire types (I to VI) and the above mentioned SAGAT query list (1.1 to 3.4). The blue crosses (X) indicate the condition by the time of simulation freezing, and the blue shapes ( ) the tolerance to be considered correct answer.

Questionnaire type I

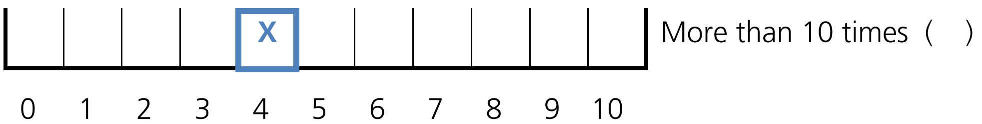
I.1.1 Enter the axis/direction of the trainee pilot input (last 3 s).



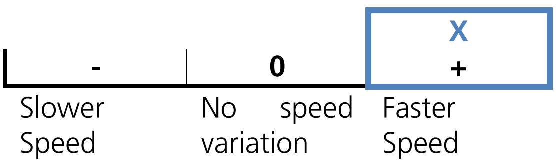
I.1.6 Enter the last light that turned on.

FIRE	LOW FUEL 1	ROTOR RPM	LOW FUEL 2
BAT TEMP	BAT DISCH	XMSN OIL P	CARGO SMOKE
STBY HOR	FCS	HIGH NR	MASTER CAUTION

I.2.3 Enter the number of times that the helicopter has flown out of the heading tolerance.

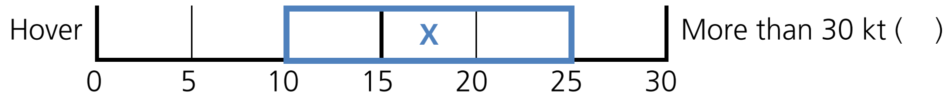


I.3.2 In the next 5 s, which variation in speed do you expect?

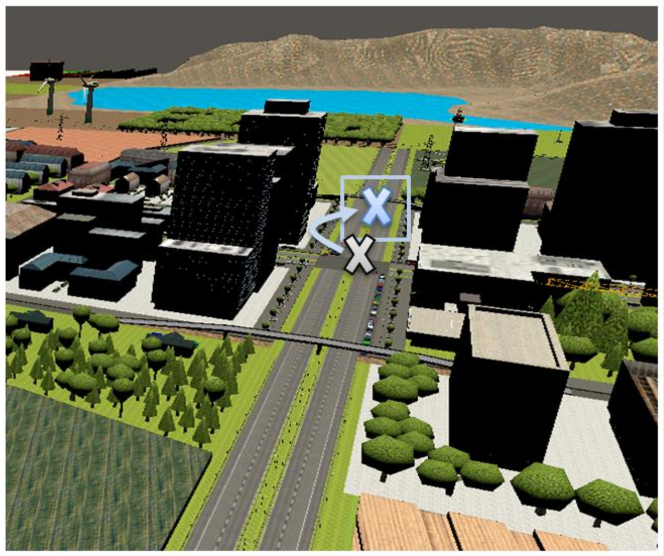


Questionnaire type II

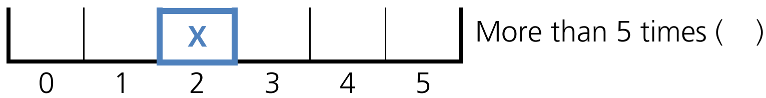
II.1.3 Enter the speed of the helicopter in knots.



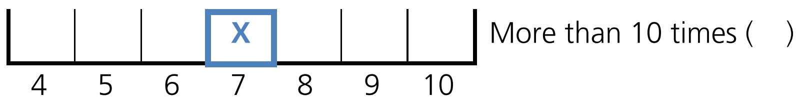
II.3.4 In the next 5 s, what is the future position of the helicopter? Indicate the current and the future position on the scene.



II.2.4 Enter the number of times that the helicopter has flown out of the height tolerance.

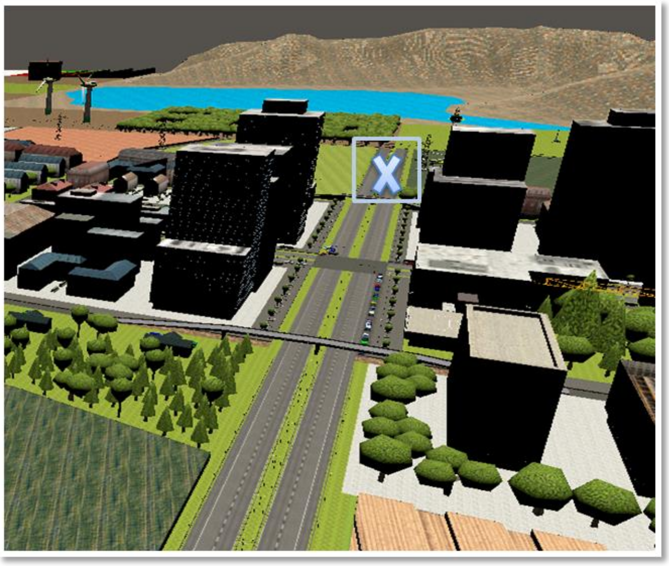


II.2.5 Enter the total number of lights on.



Questionnaire type III

III.1.2 Enter the helicopter current position.



III.2.2 Enter the number of times that the helicopter has flown out of the speed tolerance.

		X			
0	1	2	3	4	5

More than 5 times ( )

IV.3.1 Which is the recommended control input to maintain the helicopter within the tolerance performance?

Control	Input Correction	
Pitch Cyclic→	◯ Forward	⊗ Backward
Roll Cyclic→	◯ Leftward	◯ Rightward
Collective→	⊗ Upward	◯ Downward
Pedals→	◯ Left	◯ Right

III.3.3 In the next 5 s, which variation in height do you expect?

		X
-	**0**	**+**
Decrease Height	No Height variation	Increase Height

Questionnaire type IV

IV.1.4 Enter the heading of the helicopter.

( ) Less than 200° | X | More than 260° ( )

200° 210° 220° 230° 240° 250° 260

or

( ) Less than 020° | X | More than 080° ( )

020° 030° 040° 050° 060° 070° 080

IV.3.1 Which is the recommended control input to maintain the helicopter within the tolerance performance?

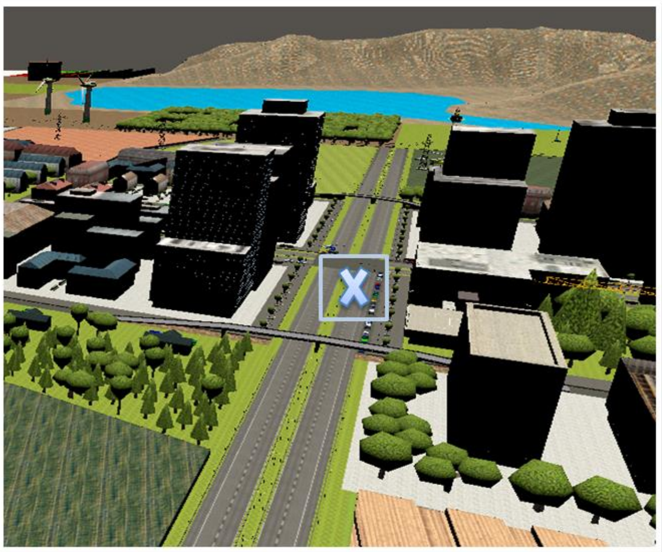
Control	Input Correction	
Pitch Cyclic→	◯ Forward	◯ Backward
Roll Cyclic→	☒ Leftward	◯ Rightward
Collective→	◯ Upward	◯ Downward
Pedals→	◯ Left	◯ Right

IV.1.5 Enter the height of the helicopter in feet.

( ) Less than 20 ft | X | More than 80 ft ( )

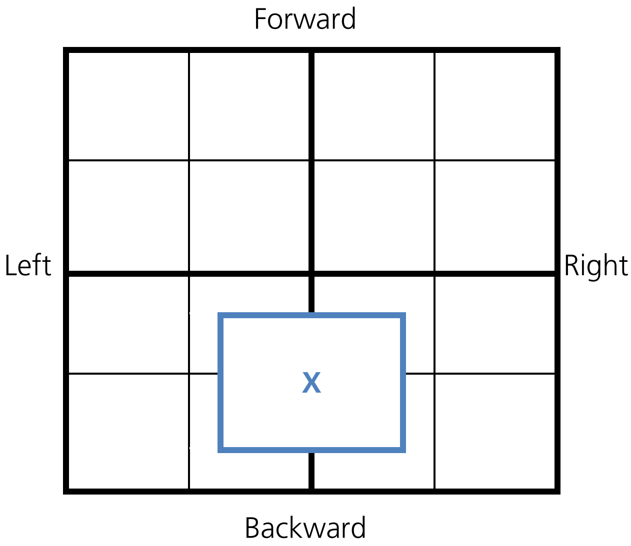
20 30 40 50 60 70 80

IV.2.1 Enter the nearest/ most critical obstacle (last 3 s).



Questionnaire type V

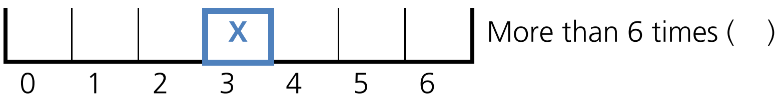
V.1.1 Enter the axis/direction of the trainee pilot input (last 3 s).



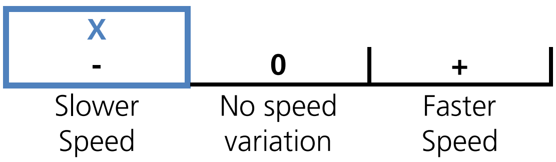
V.1.6 Enter the last light that turned on.

○ FIRE	○ LOW FUEL 1	○ ROTOR RPM	○ LOW FUEL 2
○ BAT TEMP	○ BAT DISCH	○ XMSN OIL P	○ CARGO SMOKE
○ STBY HOR	⊗ FCS	○ HIGH NR	○ MASTER CAUTION

V.2.3 Enter the number of times that the helicopter has flown out of the heading tolerance.



V.3.2 In the next 5 s, which variation in speed do you expect?



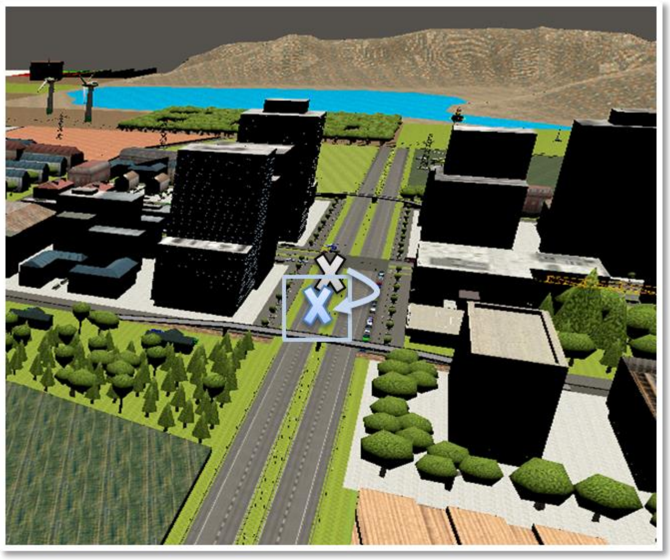
Questionnaire type VI

VI.1.3 Enter the speed of the helicopter in knots.

Hover X More than 30 kt ( )

0 5 10 15 20 25 30

VI.3.4 In the next 5 s, what is the future position of the helicopter? Indicate the current and the future position on the scene.



VI.2.5 Enter the total number of lights on.

X More than 10 times ( )

4 5 6 7 8 9 10

D.2 Transient Rating Scale

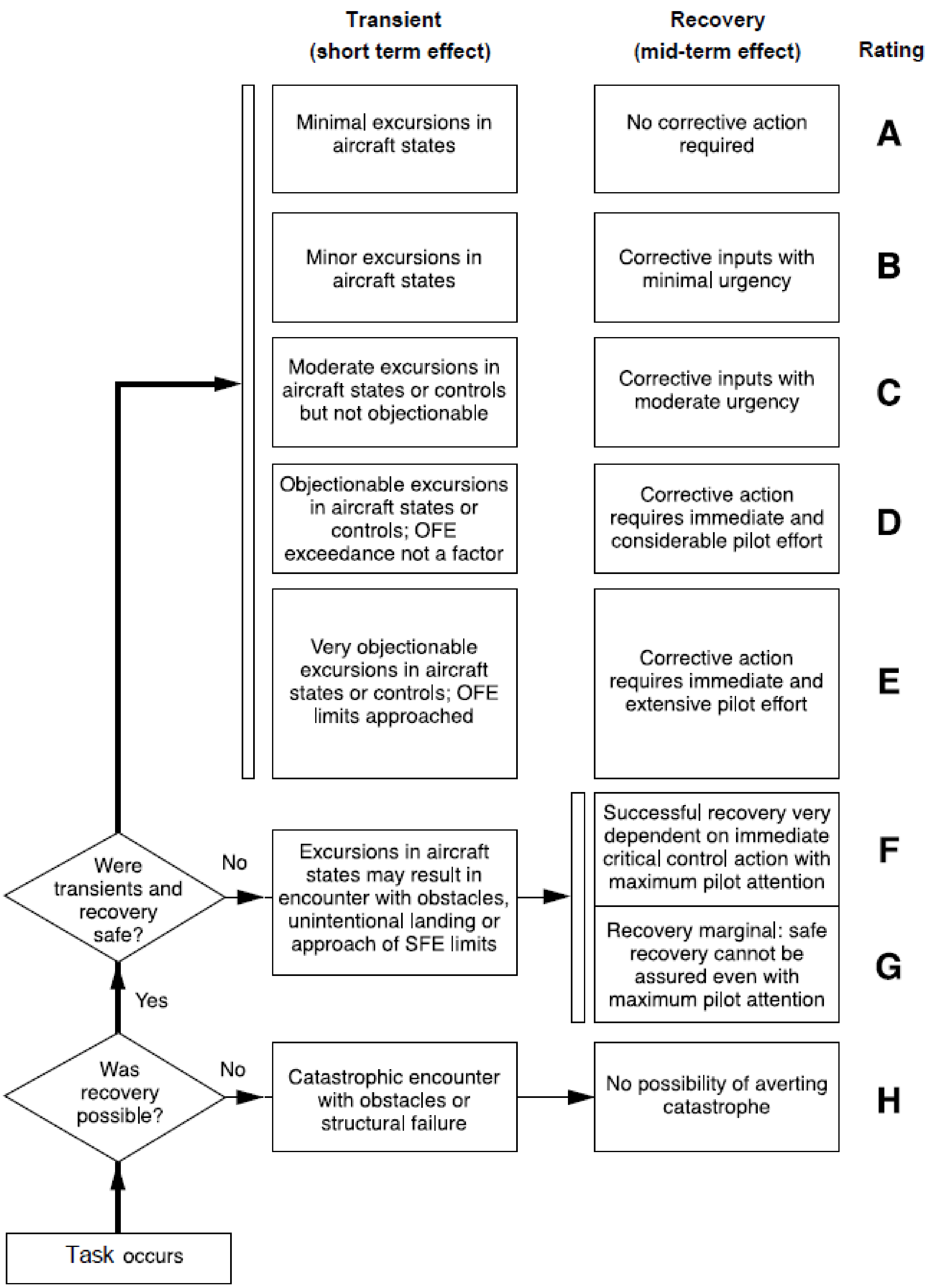


Figure D.1: Transient and recovery rating scale [142]

D.3 Integrated Transient Classification

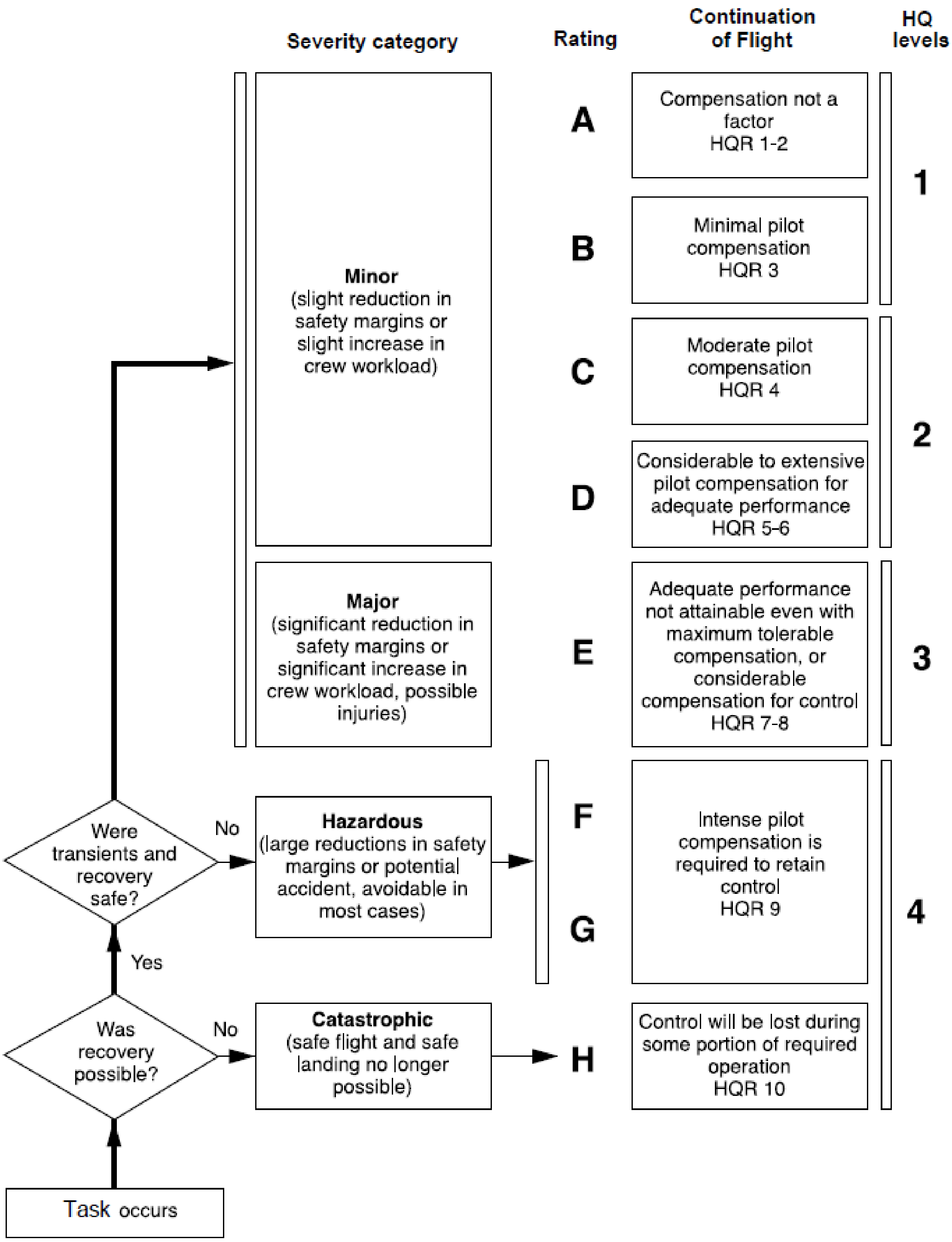


Figure D.2: Integrated transient classification

D.4 Cooper–Harper Rating Scale

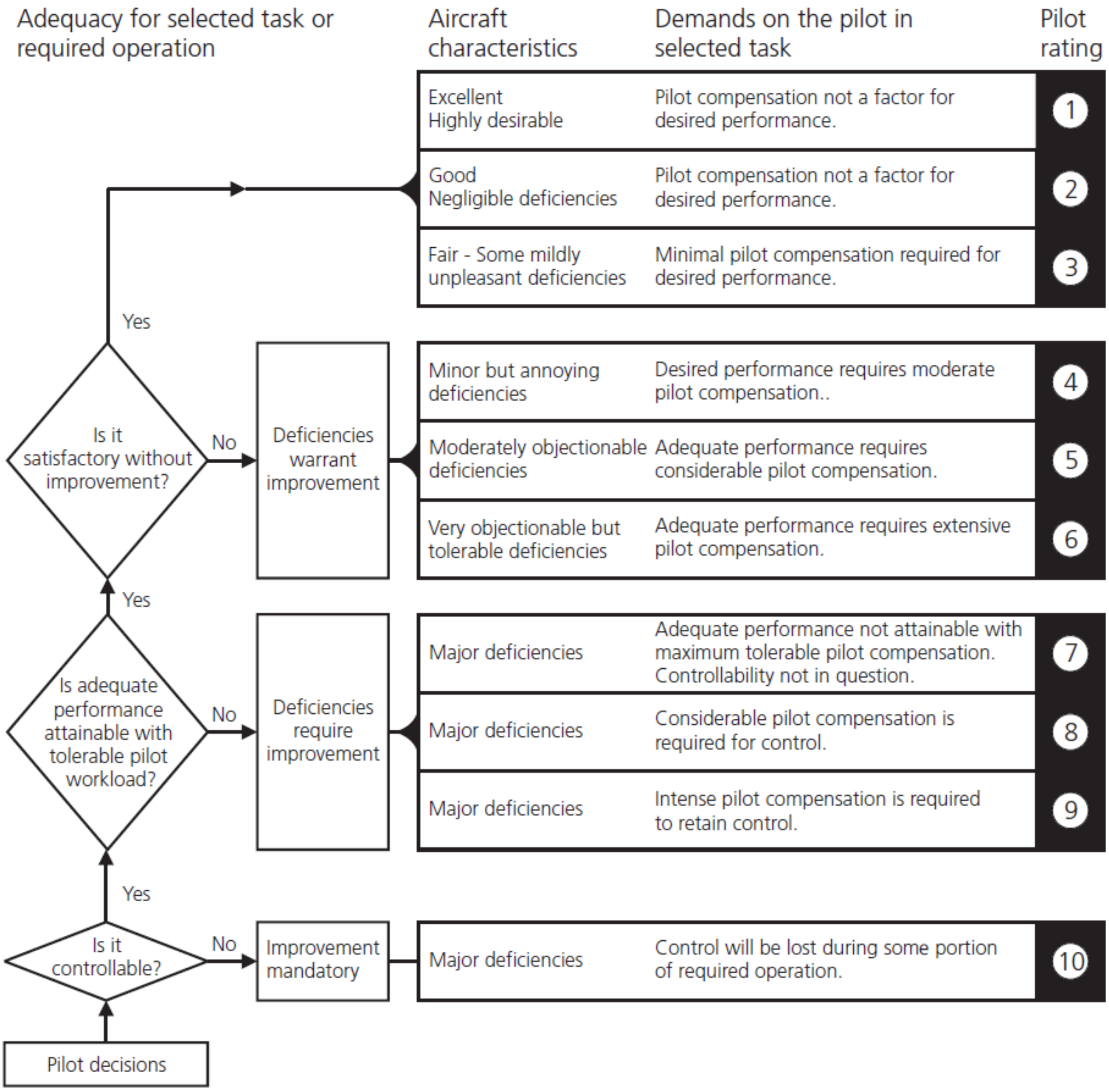


Figure D.3: Cooper–Harper handling qualities rating scale [139]

D.5 PIO Rating Scale

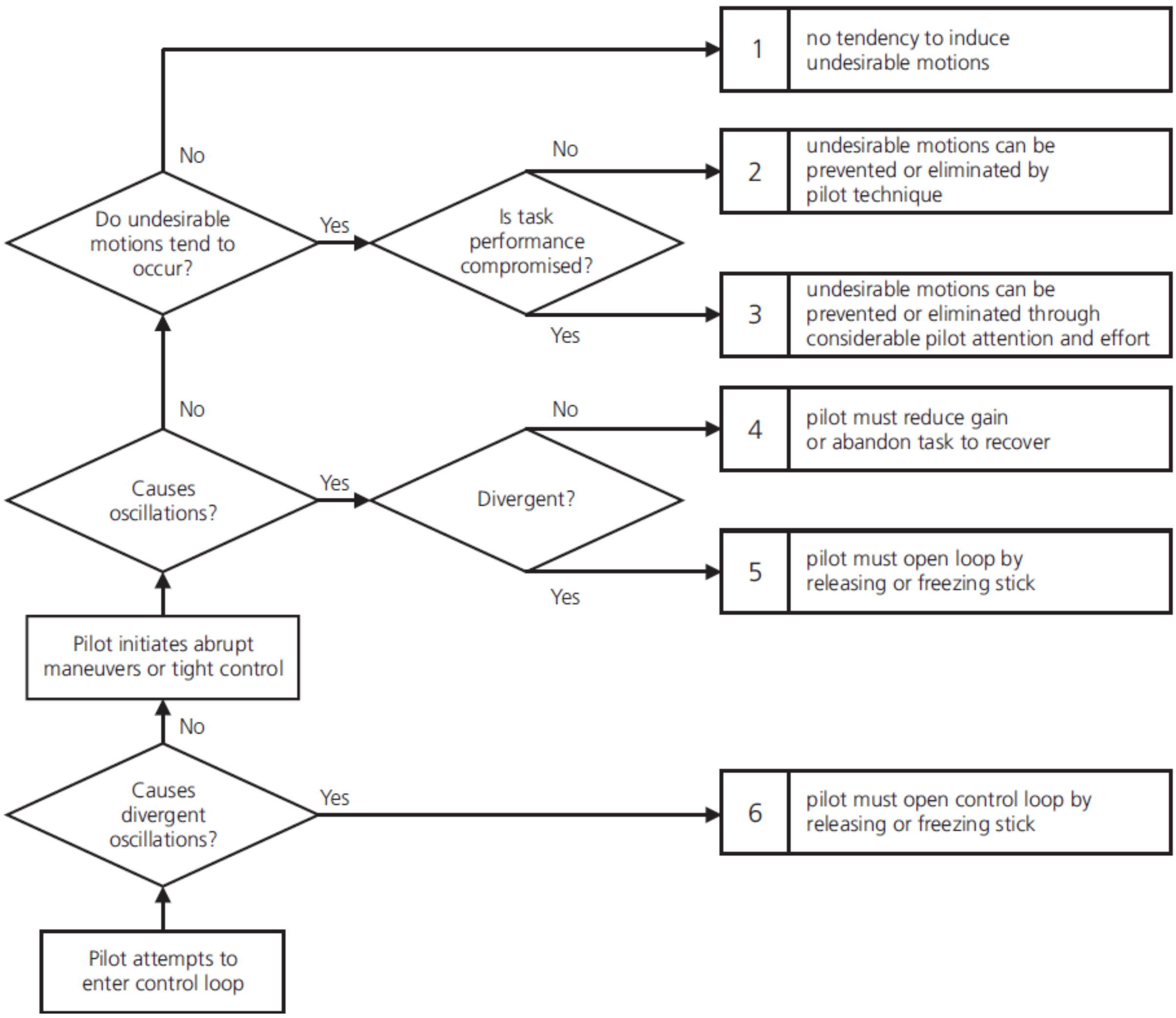
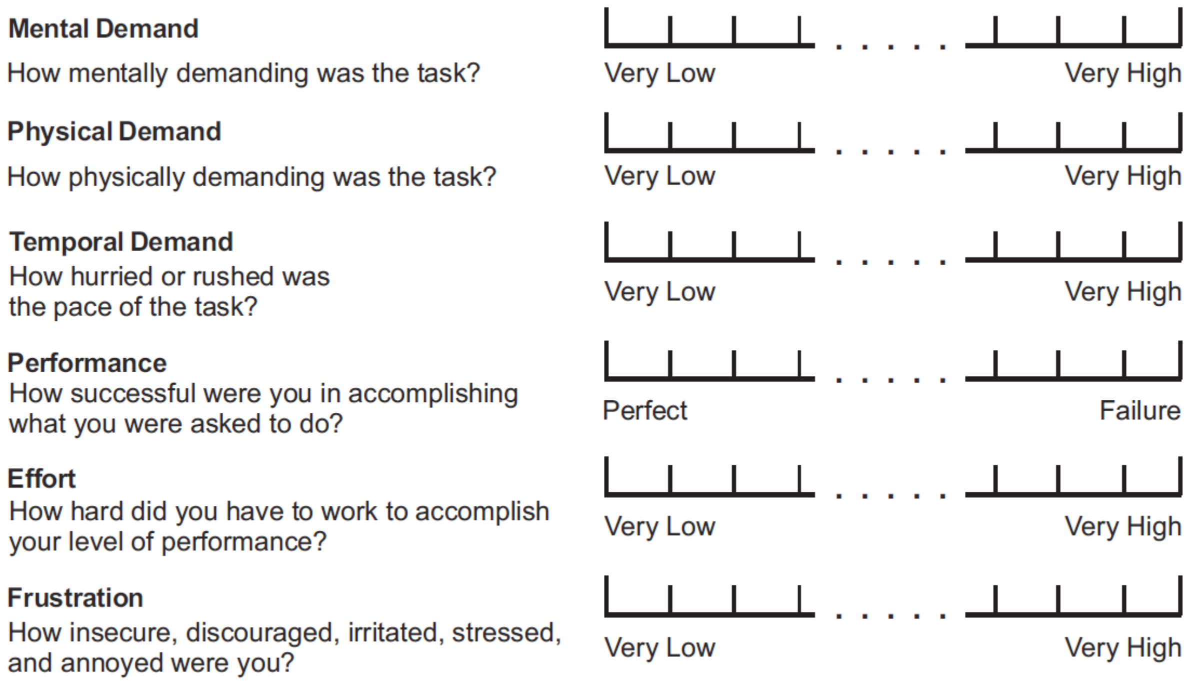


Figure D.4: PIO rating scale [143]

D.6 NASA Task Load Index


Mental Demand
How mentally demanding was the task?
Very Low — Very High

Physical Demand
How physically demanding was the task?
Very Low — Very High

Temporal Demand
How hurried or rushed was the pace of the task?
Very Low — Very High

Performance
How successful were you in accomplishing what you were asked to do?
Perfect — Failure

Effort
How hard did you have to work to accomplish your level of performance?
Very Low — Very High

Frustration
How insecure, discouraged, irritated, stressed, and annoyed were you?
Very Low — Very High

Figure D.5: NASA Task Load Index [164]

Table D.3: NASA Task Load Index description [164]

Sub-Scale	Endpoints	Descriptions
Mental Demand (MD)	Low/High	How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?
Physical Demand (PD)	Low/High	How much physical active was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
Temporal Demand (TD)	Low/High	How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?
Performance (OP)	Good/Poor	How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?
Effort (EF)	Low/High	How hard did you have to work (mentally and physically) to accomplish your level of performance?
Frustration Level (FR)	Low/High	How insecure, discouraged, irritated, stressed, and annoyed versus secure, gratified, content, relaxed, and complacent did you feel during the task?

D.7 Acceptance Scale

Table D.4: Acceptance Scale [168]

Item	5-Point Scale					Mirrored Item	Dimension
Useful						Useless	Usefulness
Pleasant						Unpleasant	Satisfying
Bad						Good	Usefulness
Nice						Annoying	Satisfying
Effective						Superfluous	Usefulness
Irritating						Likeable	Satisfying
Assisting						Worthless	Usefulness
Undesirable						Desirable	Satisfying
Raising alertness						Sleep-inducing	Usefulness

D.8 Interview

Question 1:

In terms of flight safety, how do you order the inceptor coupling configurations from 1 to 3 for the task of takeover control? Please, justify your answer.
(“1” represents the highest safety, “3” represents the least relevant for safety)

Configuration 1 ( ) Configuration 2 ( ) Configuration 3 ( )

Question 2:

From the instructor pilot perspective, the electronic inceptor coupling provides the ability to monitor the performance of the trainee pilot using the configuration 1. Please, justify your answer.

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
( )	( )	( )	( )	( )

Question 3:

In case of inappropriate inputs in low level training flight, the variable inceptor coupling system can assist the instructor pilots to takeover control considering the possibility to use the… (please, justify your answer)

a) <u>Configuration 2</u>

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
( )	( )	( )	( )	( )

b) <u>Configuration 3</u>

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
( )	( )	( )	( )	( )

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Appendix E Evaluations Supplementary Results

This appendix presents the additional results of the chapters 6 to 8, which are structured as:

- E.1 Supplementary results of the situation awareness test (answers to the SAGAT questionnaire)
- E.2 Supplementary results of the force threshold assessment (phase I, phase II, and phase III)
- E.3 Supplementary results of the system validation (analysis of transients, pilot workload, pilot acceptance, and interview comments)

E.1 Supplementary Results of the Situation Awareness Test

This section of the appendix presents results of each pilot to the SAGAT questionnaire.

Table E.1: SAGAT questionnaire - pilot A

SA Level	Number #	Number of Queries	Coupled Inceptors		Uncoupled Inceptors	
			Right	Wrong	Right	Wrong
1	1	2	**2**	0	**2**	0
	2	1	**1**	0	**1**	0
	3	2	**2**	0	**2**	0
	4	1	**1**	0	**1**	0
	5	1	0	**1**	0	**1**
	6	2	**2**	0	**1**	**1**
2	7	1	**1**	0	**1**	0
	8	1	**1**	0	**1**	0
	9	2	**2**	0	**1**	**1**
	10	1	**1**	0	**1**	0
	11	2	**2**	0	**2**	0
3	12	2	**2**	0	**1**	**1**
	13	2	**2**	0	**2**	0
	14	1	**1**	0	0	**1**
	15	2	**2**	0	**2**	0
Total		23	**22**	**1**	**18**	**5**

Table E.2: SAGAT questionnaire - pilot B

SA Level	Number #	Number of Queries	Coupled Inceptors		Uncoupled Inceptors	
			Right	Wrong	Right	Wrong
1	1	2	**2**	0	0	**2**
	2	1	**1**	0	**1**	0
	3	2	**2**	0	**2**	0
	4	1	**1**	0	**1**	0
	5	1	**1**	0	**1**	0
	6	2	**1**	**1**	**2**	0
2	7	1	**1**	0	**1**	0
	8	1	**1**	0	0	**1**
	9	2	0	**2**	**1**	**1**
	10	1	0	**1**	0	**1**
	11	2	0	**2**	0	**2**
3	12	2	**2**	0	0	**2**
	13	2	**2**	0	**2**	0
	14	1	**1**	0	**1**	0
	15	2	**1**	**1**	**1**	**1**
Total		23	**16**	**7**	**13**	**10**

Table E.3: SAGAT questionnaire - pilot C

SA Level	Number #	Number of Queries	Coupled Inceptors		Uncoupled Inceptors	
			Right	Wrong	Right	Wrong
1	1	2	1	1	0	2
	2	1	1	0	1	0
	3	2	1	1	1	1
	4	1	1	0	1	0
	5	1	1	0	1	0
	6	2	2	0	2	0
2	7	1	1	0	1	0
	8	1	1	0	1	0
	9	2	2	0	1	1
	10	1	0	1	0	1
	11	2	2	0	1	1
3	12	2	2	0	0	2
	13	2	2	0	2	0
	14	1	1	0	1	0
	15	2	2	0	1	1
Total		23	20	3	14	9

E.2 Supplementary Results of the Force Threshold Assessment

This section of the appendix presents the results of the force threshold assessment, including the phase I (Table E.4 and Table E.5), phase II (Table E.6 to Table E.9), and phase III (Table E.10 to Table E.12).

Table E.4: Control deflection variation divided by force threshold and Counter Force

Counter Force off

	Control Deflection Variation [%]				
	20 N	25 N	30 N	35 N	40 N
1	29.2	36.3	30.2	34.1	48.0
2	24.9	27.3	38.9	31.2	43.6
3	27.3	35.9	37.1	32.4	46.2
4	30.4	24.8	31.2	32.8	46.7
5	26.6	28.3	32.3	32.7	40.9
6	26.6	25.4	35.8	39.5	43.8
7	27.8	31.6	36.4	40.0	40.3
8	30.7	38.5	35.3	38.5	43.0
9	31.3	38.3	32.3	37.8	43.5
10	29.7	36.7	33.0	32.1	39.9
11	25.4	33.0	35.1	36.5	38.1
12	27.1	32.5	36.7	35.1	40.9
13	28.6	30.1	33.5	37.2	39.6
14	25.9	31.9	36.6	40.8	43.0
15	28.5	30.2	36.9	33.6	36.3
16	28.7	35.2	30.9	38.9	35.9
17	25.8	30.4	35.7	38.2	36.2
18	23.3	35.3	29.5	41.4	38.3
19	28.9	27.1	33.3	35.3	38.4
20	23.4	33.0	36.5	36.1	37.5

Counter Force on

	Control Deflection Variation [%]				
	20 N	25 N	30 N	35 N	40 N
1	13.2	9.9	13.1	14.7	16.8
2	12.7	9.0	13.1	15.3	16.6
3	12.2	12.7	9.5	14.4	12.9
4	11.2	9.1	14.2	14.5	15.7
5	5.8	13.8	16.1	15.6	14.9
6	5.9	10.7	14.8	14.6	12.5
7	11.3	12.1	16.8	18.7	19.7
8	9.3	14.4	17.3	16.2	14.9
9	12.0	10.8	10.0	16.4	12.5
10	10.8	13.8	13.9	14.1	13.2
11	10.4	8.4	9.5	12.7	12.4
12	8.3	9.7	15.2	12.0	15.7
13	7.9	12.3	14.7	14.6	16.1
14	8.3	12.2	16.1	11.2	20.4
15	12.0	15.6	12.0	17.0	19.9
16	6.4	12.5	16.4	15.6	17.9
17	6.3	10.3	17.2	12.3	17.7
18	10.4	11.8	10.3	13.2	18.6
19	11.3	12.4	9.6	11.8	18.8
20	12.0	9.3	16.9	12.5	18.2

Table E.5: Pitch attitude variation divided by force threshold and Counter Force

Counter Force off

Pitch Attitude Variation [deg]					
#	20 N	25 N	30 N	35 N	40 N
1	13.0	12.6	12.7	14.6	18.7
2	11.6	11.9	16.7	15.2	16.1
3	14.6	13.4	13.6	18.4	20.8
4	10.9	11.8	14.7	15.8	19.4
5	11.5	12.0	17.1	20.0	19.5
6	12.8	13.0	16.8	16.3	16.6
7	12.0	13.5	16.0	17.1	17.1
8	13.6	16.0	15.6	13.4	20.7
9	11.7	15.6	15.1	15.0	15.0
10	11.9	11.4	15.0	13.0	14.2
11	11.4	15.0	17.7	16.1	14.6
12	10.6	13.6	16.1	12.7	16.0
13	12.7	11.7	13.4	13.6	14.3
14	13.8	12.5	12.5	15.2	13.1
15	12.8	12.2	16.4	16.9	13.4
16	12.2	12.5	12.5	13.0	17.0
17	10.7	11.4	13.4	16.6	14.1
18	12.2	14.1	13.0	18.4	16.5
19	12.0	11.8	13.0	13.7	15.5
20	10.9	11.3	13.5	15.8	17.0

Counter Force on

Pitch Attitude Variation [deg]					
#	20 N	25 N	30 N	35 N	40 N
1	8.1	7.1	7.5	8.5	9.9
2	8.8	6.9	8.8	8.6	10.1
3	8.7	8.7	7.8	9.6	8.7
4	6.5	9.1	7.8	9.9	7.7
5	6.8	7.9	7.3	7.6	8.5
6	6.1	7.8	8.9	10.0	8.8
7	7.3	8.6	7.9	7.2	10.4
8	9.1	8.4	8.8	9.2	8.8
9	7.0	8.8	9.6	7.7	8.1
10	6.4	7.2	7.2	7.8	7.6
11	6.7	7.2	6.5	7.3	7.6
12	7.5	7.7	6.9	8.2	7.3
13	6.4	7.4	8.8	8.2	7.0
14	6.6	8.0	8.2	8.1	7.6
15	8.9	7.5	7.6	9.1	7.8
16	6.0	8.4	8.7	7.5	9.6
17	5.9	6.7	8.2	7.8	7.8
18	6.1	6.2	6.4	8.3	9.5
19	5.5	6.0	6.7	7.2	8.2
20	6.6	6.1	8.5	7.5	7.2

Table E.6: RMS control deflection in the force threshold assessment (phase II)

Counter Force off

RMS Control Deflection [%]			
#	20 N	30 N	40 N
1	68.6	50.1	89.0
2	64.5	42.0	84.3
3	39.6	6.4	82.8
4	10.8	37.5	75.2
5	11.4	23.3	36.6
6	29.4	31.7	68.2
7	37.1	20.2	92.1
8	41.9	25.1	68.4
9	29.0	65.0	31.9
10	45.8	47.1	49.7
11	41.2	38.6	64.5
12	70.6	55.3	50.0
13	74.5	55.4	81.2
14	41.4	60.1	54.0
15	79.4	42.8	69.4

Counter Force on

RMS Control Deflection [%]			
#	20 N	30 N	40 N
1	0.9	1.2	8.9
2	3.9	1.6	11.0
3	2.1	3.9	6.6
4	2.0	10.8	9.5
5	1.0	4.0	8.7
6	6.0	3.4	16.6
7	1.2	1.7	37.1
8	2.3	0.3	32.9
9	6.9	6.9	57.0
10	4.2	7.2	47.5
11	6.5	8.1	51.7
12	8.9	5.5	24.5
13	7.9	14.3	27.7
14	2.5	5.7	19.5
15	5.5	4.5	46.5

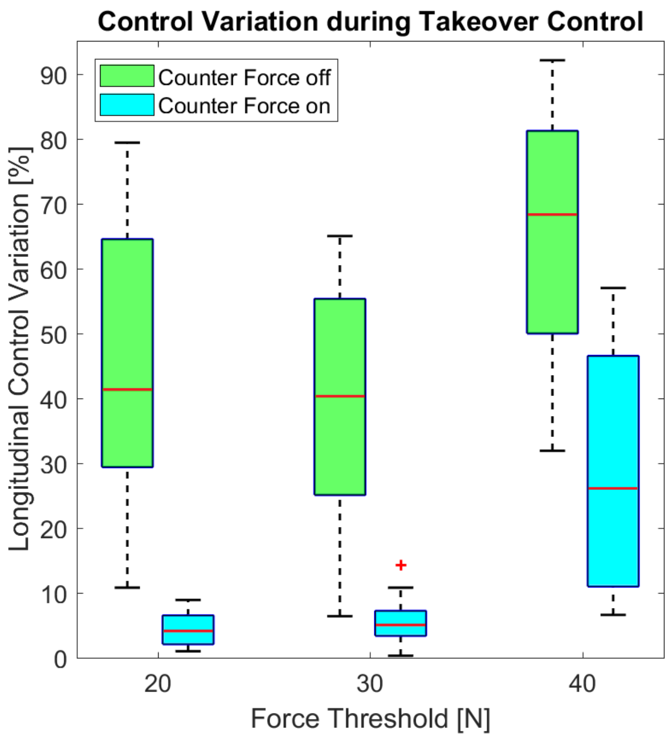

Figure E.1: Boxplot of RMS control deflection for the modified helicopter

Table E.7: Pitch attitude variation in the force threshold assessment (phase II)

	Counter Force off				Counter Force on		
	Pitch Attitude Variation [deg]				Pitch Attitude Variation [deg]		
#	20 N	30 N	40 N	#	20 N	30 N	40 N
1	27.0	26.0	28.2	1	8.8	8.2	25.4
2	24.8	21.4	29.8	2	11.5	11.7	21.5
3	24.5	25.5	27.7	3	8.4	12.0	22.3
4	20.9	23.0	25.7	4	9.4	7.2	16.7
5	16.3	18.5	26.3	5	10.0	10.6	19.4
6	20.1	28.5	22.3	6	6.9	18.1	18.2
7	20.7	22.6	34.6	7	7.8	12.2	16.5
8	20.6	26.4	28.7	8	11.0	12.0	19.8
9	15.9	33.0	20.3	9	14.2	11.8	25.3
10	17.9	15.1	21.3	10	9.2	10.9	26.1
11	30.2	25.9	33.8	11	16.4	18.9	27.8
12	33.4	18.8	28.7	12	17.2	8.5	23.4
13	29.6	32.9	31.9	13	12.8	18.8	28.9
14	33.1	24.9	32.3	14	13.2	14.4	31.2
15	19.7	29.0	41.3	15	19.4	17.4	22.5

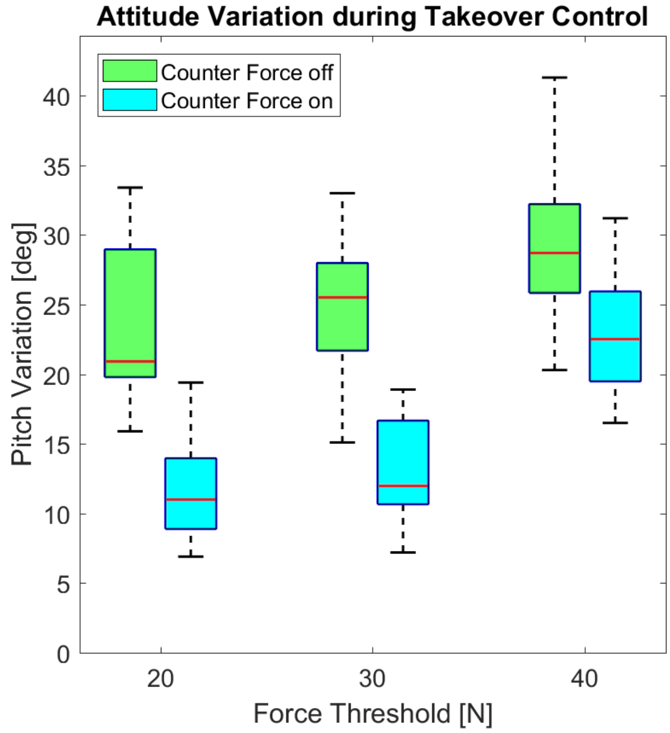

Figure E.2: Boxplot of attitude variation for the modified helicopter

Table E.8: Normality test

Parameter	Force Threshold – Counter Force	Statistic	df	Sig.[1]
RMS Longitudinal Control Deflection	20 N – Counter Force Off	0.932	15	0.291
	20 N – Counter Force On	0.922	15	0.205
	30 N – Counter Force Off	0.975	15	0.920
	30 N – Counter Force On	0.934	15	0.311
	40 N – Counter Force Off	0.946	15	0.470
	40 N – Counter Force On	0.904	15	0.111
Pitch Attitude Variation	20 N – Counter Force Off	0.921	15	0.199
	20 N – Counter Force On	0.934	15	0.317
	30 N – Counter Force Off	0.972	15	0.881
	30 N – Counter Force On	0.906	15	0.116
	40 N – Counter Force Off	0.966	15	0.803
	40 N – Counter Force On	0.971	15	0.872

[1] Shapiro-Wilk method [172]

Result: significance values (*p*-values) are higher than the alpha level of 0.05; therefore, the null hypothesis that the data came from a normally distributed population is not rejected. Thus, the data tested are normally distributed.

Table E.9: Transient rating (phase II)

Counter Force off

Transient Rating			
#[1]	20 N	30 N	40 N
1	E	E	F
2	E	E	E
3	E	C	F
4	C	E	F
5	D	E	D
6	D	E	E
7	E	E	F
8	E	E	F
9	E	F	E
10	E	F	E
11	E	E	F
12	F	E	F
13	E	F	F
14	E	F	F
15	E	F	F

Counter Force on

Transient Rating			
#[1]	20 N	30 N	40 N
1	A	B	D
2	C	A	D
3	B	B	D
4	B	C	C
5	B	B	C
6	C	C	D
7	B	C	E
8	B	A	E
9	C	C	E
10	B	C	E
11	B	C	F
12	C	D	E
13	C	D	E
14	B	D	E
15	B	C	E

[1] The test point number corresponds to the numbers of the Table E.6 and Table E.7

Table E.10: RMS control deflection in the force threshold assessment (phase III)

	Counter Force off				Counter Force on				Decoupling off	
	RMS Control Deflection [%]				RMS Control Deflection [%]				RMS Control Deflection [%]	
HM[1]	#	20 N	30 N	40 N	#	20 N	30 N	40 N	#	220 N
B	1	13.6	29.0	44.5	1	3.8	3.4	24.7	1	25.3
	2	13.2	28.8	43.8	2	2.1	7.2	14.0	2	47.6
	3	8.3	18.3	30.1	3	1.6	2.7	2.1	3	28.5
M	4	18.9	38.2	65.7	4	2.6	4.0	30.9	4	20.7
	5	30.0	24.6	49.9	5	3.0	5.9	12.5	5	80.1
	6	6.3	7.7	28.3	6	3.2	1.8	7.0	6	12.8

[1]HM: helicopter model; B: baseline; M: modified

Table E.11: Pitch attitude variation in the force threshold assessment (phase III)

	Counter Force off				Counter Force on				Decoupling off	
	Pitch Attitude Variation [deg]				Pitch Attitude Variation [deg]				Pitch Attitude Variation [deg]	
HM[1]	#	20 N	30 N	40 N	#	20 N	30 N	40 N	#	220 N
B	1	13.7	25.3	15.3	1	8.3	11.3	18.7	1	23.0
	2	10.9	18.7	23.6	2	7.7	11.8	15.9	2	17.1
	3	9.9	17.5	13.2	3	8.8	9.5	9.5	3	12.8
M	4	15.0	23.5	22.5	4	9.5	12.6	19.9	4	13.3
	5	15.3	28.4	29.4	5	7.0	10.4	18.5	5	20.1
	6	10.6	10.7	17.8	6	8.7	10.0	10.7	6	9.8

[1]HM: helicopter model; B: baseline; M: modified

Table E.12: Handling qualities ratings

Condition	Force Threshold	Baseline Helicopter			Modified Helicopter		
		Pilot D	Pilot E	Pilot F	Pilot D	Pilot E	Pilot F
Counter Force on	20 N	4	4	6	7	7	9
	30 N	4	4	6	8	7	9
	40 N	4	5	6	8	7	9
Counter Force off	20 N	4	4	6	7	7	9
	30 N	4	5	6	7	7	9
	40 N	4	5	6	8	7	9
No Decoupling	220 N	4	4	6	9	7	9
Hover ADS	N/A	4	5	6	7	7	9

E.3 Supplementary Results of the System Validation

This section of the appendix presents the results of the system validation, including the evaluations of analysis of transients (Figure E.3 to Figure E.12), pilot workload (Table E.21 and Table E.22), pilot acceptance (Table E.23 to Table E.26), and interview comments (Table E.27 to Table E.29).

Analysis of Transients

Table E.13: Hover, roll axis, pilot G, configuration 1

Task: Hover- Run 01		
Pilot G	Date: September 20, 2017	Run Code: 144455
Configuration: 1 (BENCH)	Axis: Roll	
Takeover Control Mode: Force Fight	Force Fight time: 1.33 sec	
Coupling Force Threshold: 220 N		
Time = 0 sec (magenta dashed line): Trainee pilot releases control		

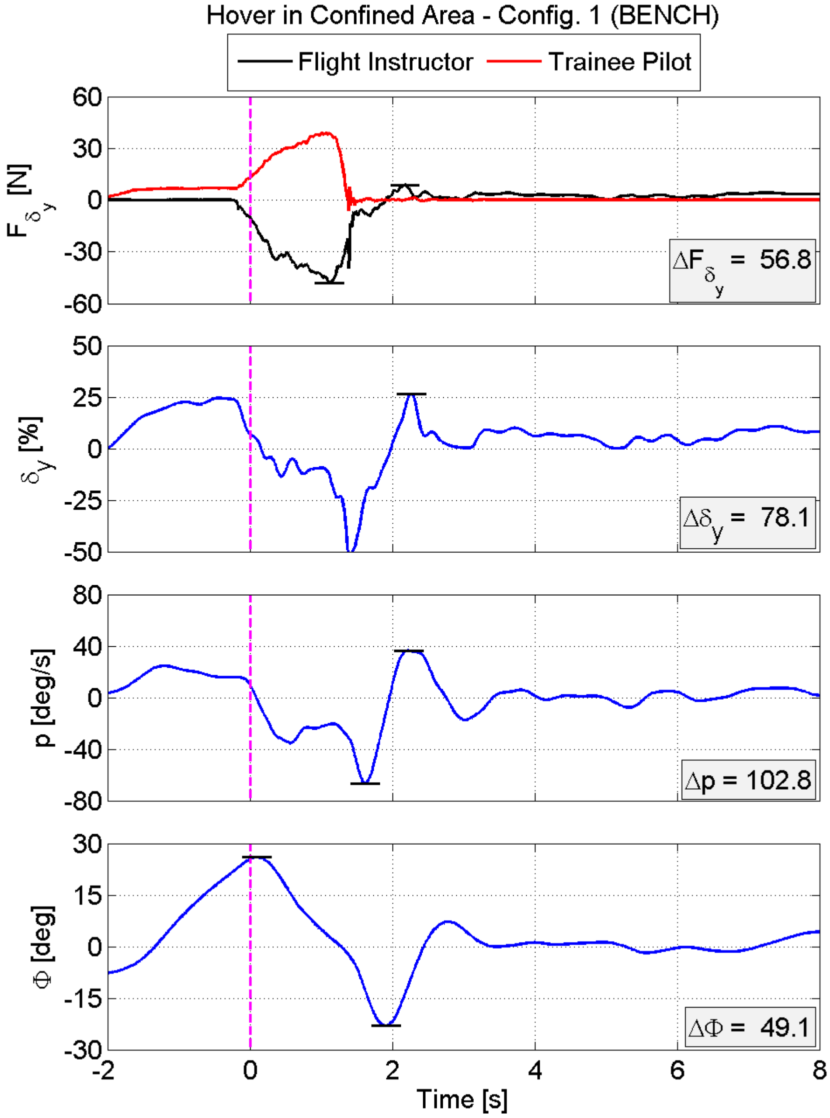

Figure E.3: Hover, roll axis, pilot G, configuration 1

Table E.14: Hover, roll axis, pilot G, configuration 2

Task: Hover- Run 06		
Pilot G	Date: September 20, 2017	Run Code: 102448
Configuration: 2 (AUTO)	Axis: Roll	
Takeover Control Mode: Force Threshold Automatic Decoupling		
Coupling Force Threshold: 30 N		
Time = 0 sec (magenta dashed line): Trainee pilot releases control		

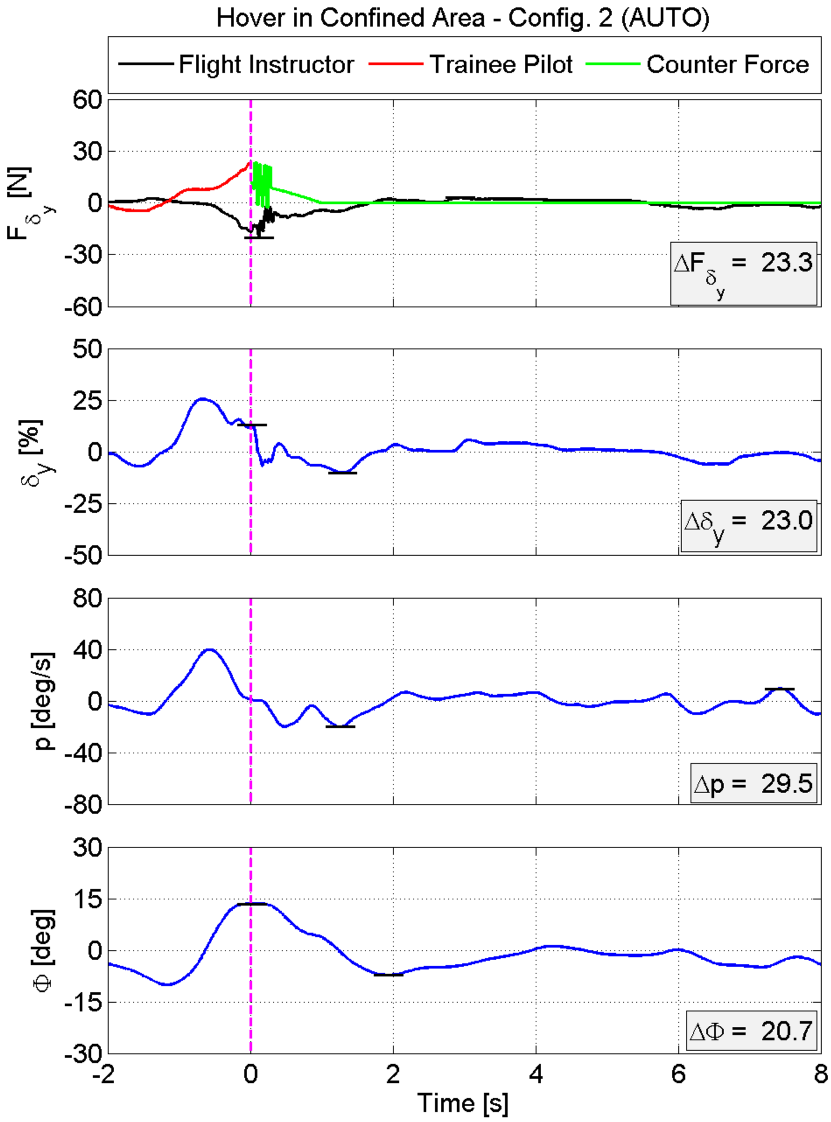

Figure E.4: Hover, roll axis, pilot G, configuration 2

Table E.15: Hover, roll axis, pilot G, configuration 3

Task: Hover- Run 11		
Pilot G	Date: September 20, 2017	Run Code: 130445
Configuration: 3 (PUSH)	Axis: Roll	
Takeover Control Mode: Pushbutton Priority		
Coupling Force Threshold: 220 N		
Time = 0 sec (magenta dashed line): Trainee pilot releases control		

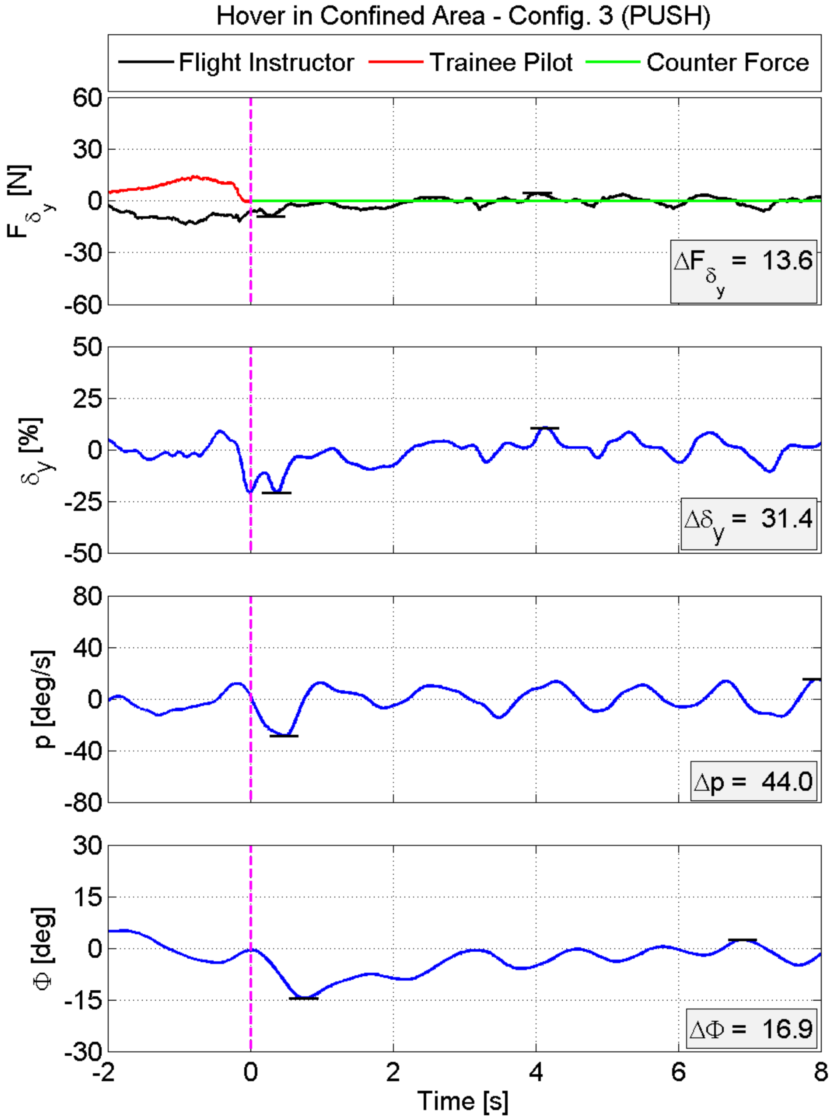

Figure E.5: Hover, roll axis, pilot G, configuration 3

Table E.16: Hover, pitch axis, pilot H, configuration 1

Task: Hover- Run 24		
Pilot H	Date: September 27, 2017	Run Code: 095225
Configuration: 1 (BENCH)	Axis: Pitch	
Takeover Control Mode: Force Fight	Force Fight time: 1.74 sec	
Coupling Force Threshold: 220 N		
Time = 0 sec (magenta dashed line): Trainee Pilot releases control		

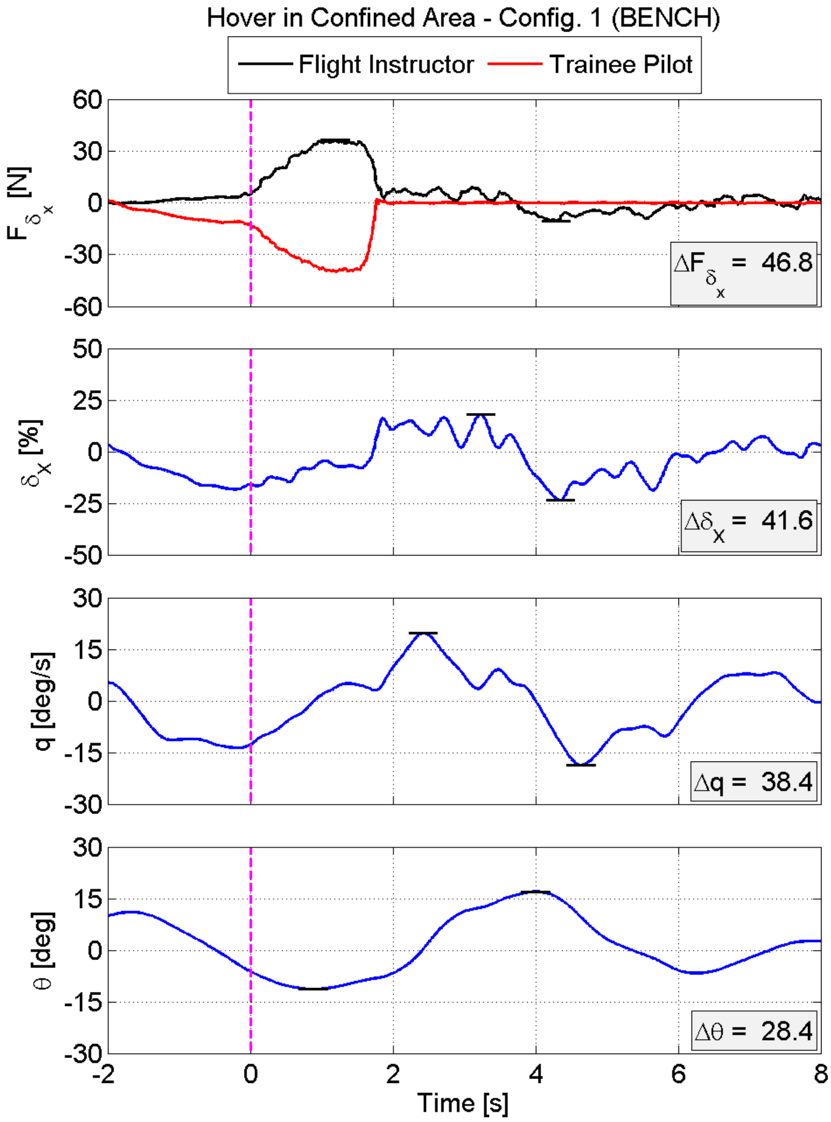

Figure E.6: Hover, pitch axis, pilot H, configuration 1

Table E.17: Hover, pitch axis, pilot H, configuration 2

Task: Hover- Run 29		
Pilot H	Date: September 27, 2017	Run Code: 090121
Configuration: 2 (AUTO)	Axis: Pitch	
Takeover Control Mode: Force Threshold Automatic Decoupling		
Coupling Force Threshold: 30 N		
Time = 0 sec (magenta dashed line): Trainee Pilot releases control		

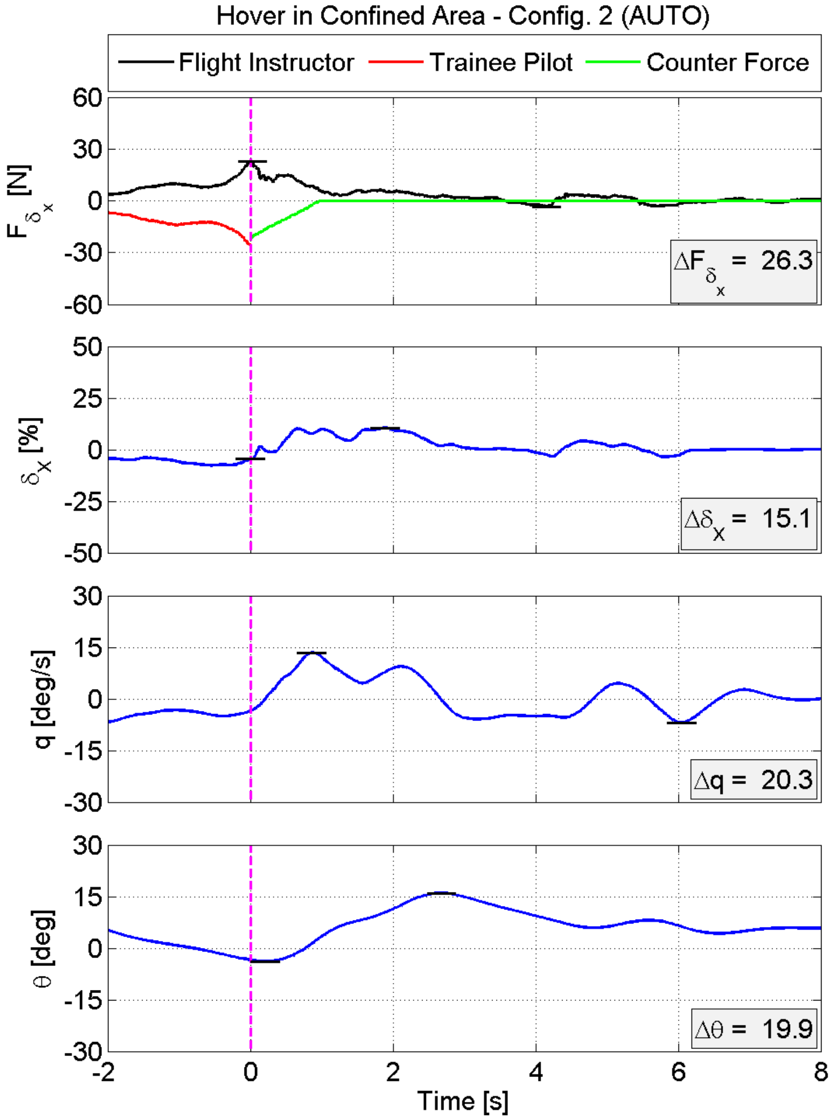

Figure E.7: Hover, pitch axis, pilot H, configuration 2

Table E.18: Hover, pitch axis, pilot H, configuration 3

Task: Hover- Run 34		
Pilot H	Date: September 27, 2017	Run Code: 084132
Configuration: 3 (PUSH)	Axis: Pitch	
Takeover Control Mode: Pushbutton Priority		
Coupling Force Threshold: 220 N		
Time = 0 sec (magenta dashed line): Trainee Pilot releases control		

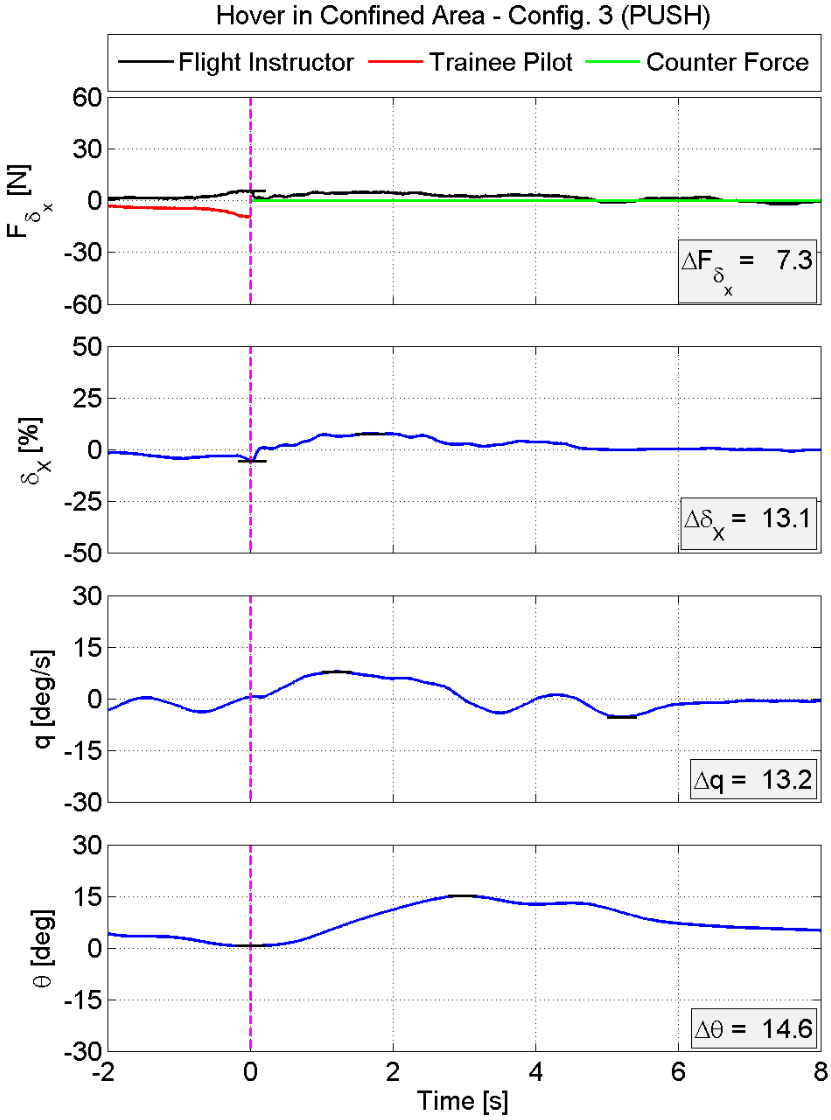

Figure E.8: Hover, pitch axis, pilot H, configuration 3

Table E.19: Hover, roll axis, pilot G, $t_{f1} = 0$

Task: Hover- Run 16		
Pilot G	Date: September 20, 2017	Run Code: 125727
Configuration: $t_{f1} = 0$	Axis: Roll	
Takeover Control Mode: Verbal Interaction		
Coupling Force Threshold: 220 N		
Time = 0 sec (magenta dashed line): Trainee pilot releases control		

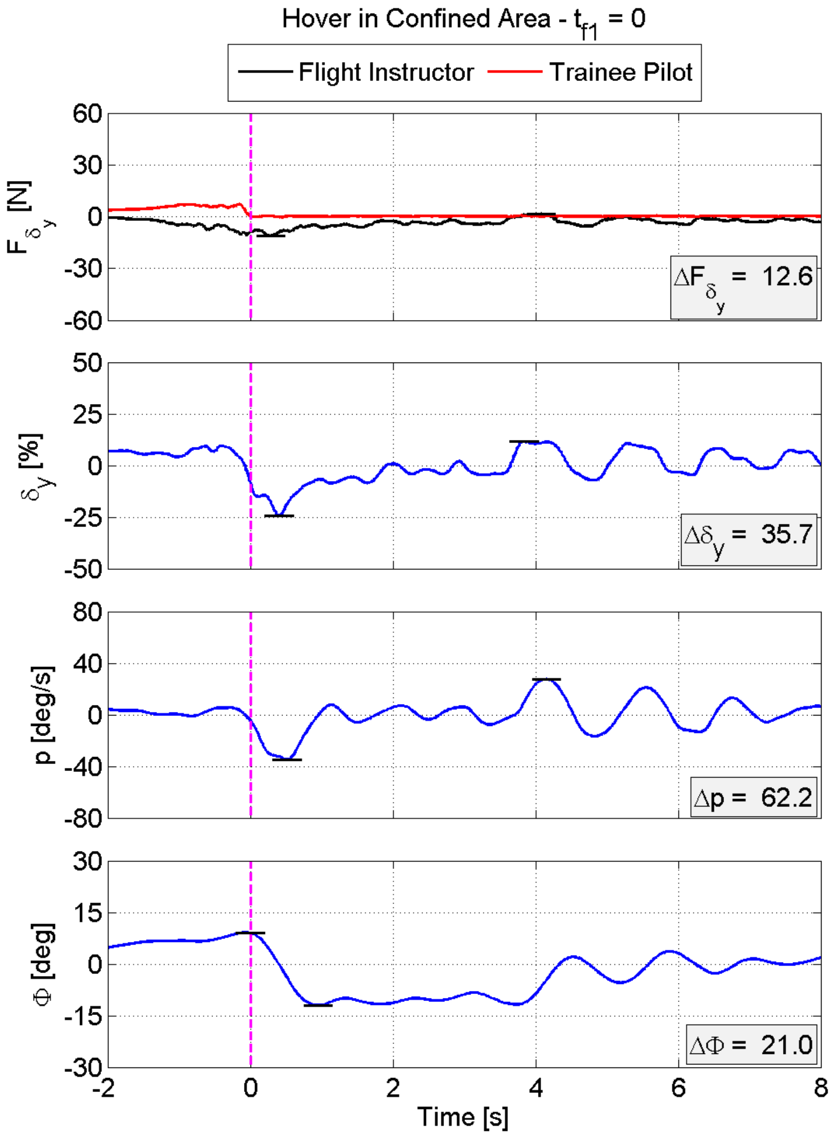

Figure E.9: Hover, roll axis, pilot G, $t_{f1} = 0$

Table E.20: Hover, pitch axis, pilot H, $t_{f1} = 0$

Task: Hover- Run 39		
Pilot H	Date: September 27, 2017	Run Code: 091441
Configuration: $t_{f1} = 0$	Axis: Pitch	
Takeover Control Mode: Verbal Interaction		
Coupling Force Threshold: 220 N		
Time = 0 sec (magenta dashed line): Trainee Pilot releases control		
Time = 8 sec (red dashed line): Interval of interest after Takeover Condition		

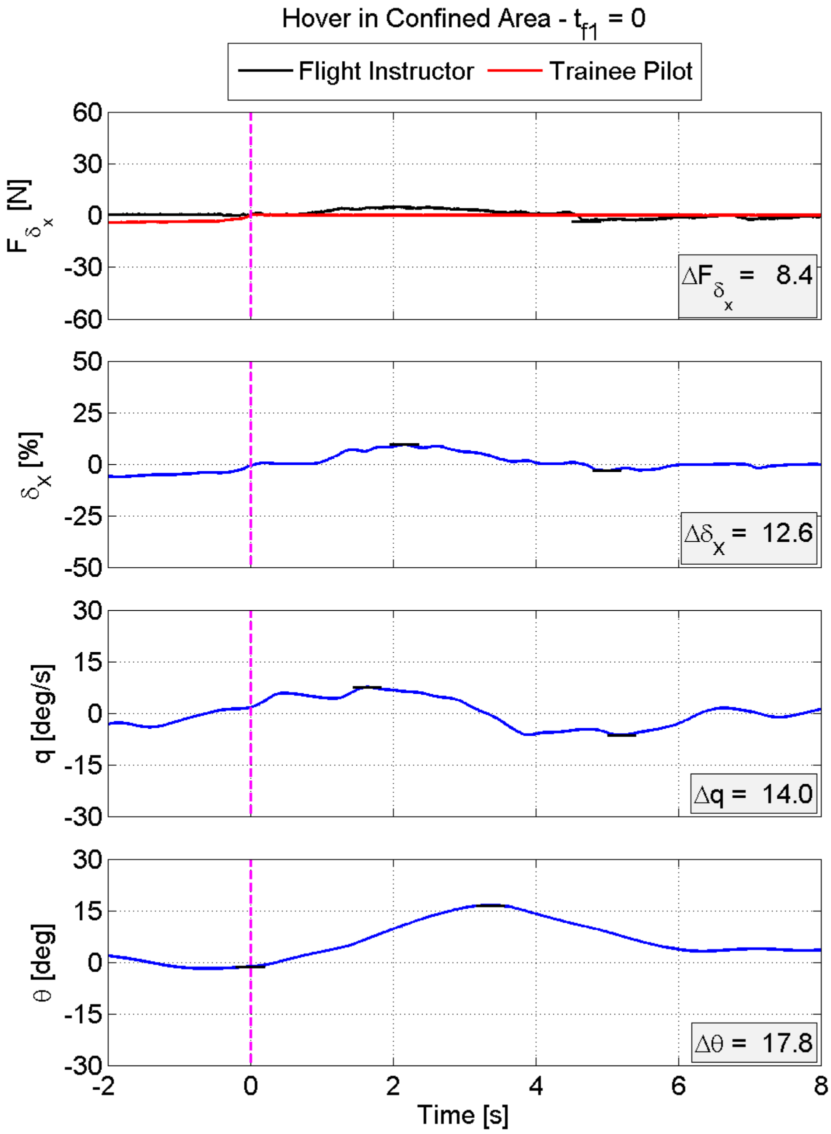

Figure E.10: Hover, pitch axis, pilot H, $t_{f1} = 0$

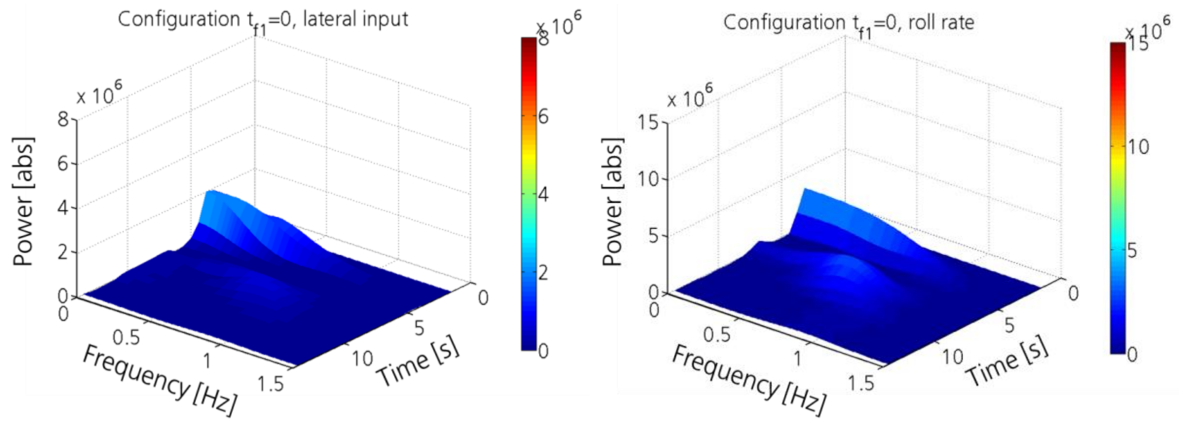

Figure E.11: Spectrogram, pitch axis, pilot G, $t_{f1} = 0$

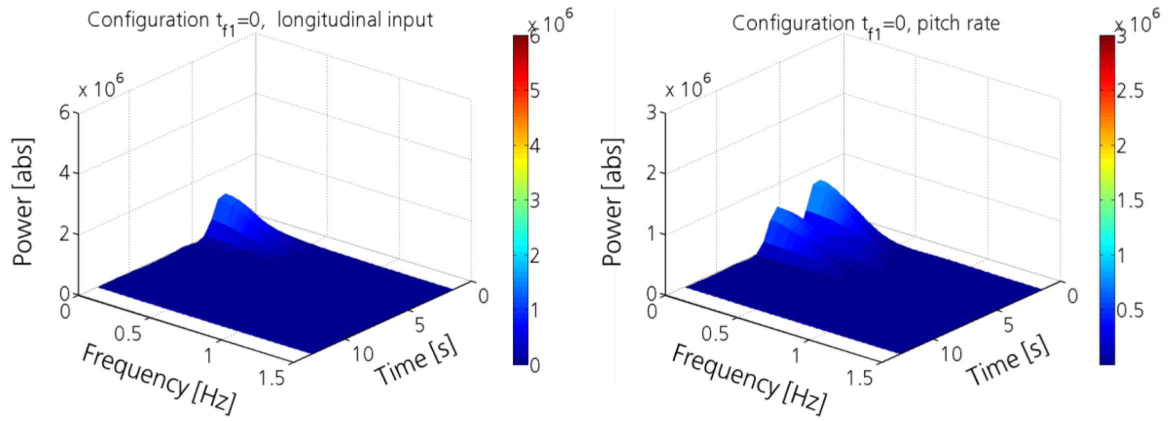

Figure E.12: Spectrogram, roll axis, pilot H, $t_{f1} = 0$

NASA TLX

Table E.21: ANOVA - overall NASA TLX

Dependent Variable		Sum of Squares	df	Mean Square	F	Sig.
Overall NASA TLX	Between Groups	1256.668	2	628.334	9.503	.003[1]
	Within Groups	793.448	12	66.121		
	Total	2050.116	14			

[1]At least one value is significant different at the 0.05 level.

Table E.22: Tukey HSD analysis - overall NASA TLX

Dependent Variable	(I) Inceptor Coupling Configuration	(J) Inceptor Coupling Configuration	Mean Difference (I-J)	Std. Error	Sig.
NASA TLX	Config. 1 BENCH	Config. 3 PUSH	20.780[1]	5.143	0.004
		Config. 2 AUTO	17.680[1]	5.143	0.013
	Config. 2 AUTO	Config. 1 BENCH	-17.680[1]	5.143	0.013
		Config. 3 PUSH	3.100	5.143	0.821
	Config. 3 PUSH	Config. 1 BENCH	-20.780[1]	5.143	0.004
		Config. 2 AUTO	-3.100	5.143	0.821

[1]The mean difference is significant at the 0.05 level.

Acceptance Scale

Table E.23: Mean ratings and standard deviations of acceptance items

	1 BENCH		2 AUTO		3 PUSH	
Item	Mean	SD[1]	Mean	SD[1]	Mean	SD[1]
useful	0.0	0.7	1.6	0.5	1.6	0.5
pleasant	-1.0	0.7	0.6	0.5	1.6	0.5
good	-0.8	0.8	1.0	0.7	1.8	0.4
nice	-0.4	0.5	0.8	0.4	1.6	0.5
effective	0.0	0.7	1.2	0.4	1.6	0.5
likeable	-0.6	0.5	0.6	1.1	0.6	1.1
assisting	-0.4	0.5	1.2	0.4	1.4	0.5
desirable	-0.4	1.1	1.0	0.7	1.6	0.5
alertness	1.6	0.9	1.4	0.5	0.8	0.4

[1]SD: standard deviation

Table E.24: Acceptance ratings of five experimental pilots

	Usefulness [rating]			Satisfying [rating]		
	Inceptor Coupling Configuration					
Experimental Pilots	1	2	3	1	2	3
Pilot A	0.0	1.8	1.2	-1.5	1.3	1.0
Pilot B	0.4	1.0	1.8	-0.3	0.8	2.0
Pilot G	0.2	1.2	1.4	-0.5	0.5	1.0
Pilot H	0.6	1.6	1.8	0.3	1.0	1.8
Pilot I	-0.8	0.8	1.0	-1.0	0.3	1.0
Total (Mean)	0.1	1.3	1.4	-0.6	0.8	1.4

Table E.25: ANOVA – usefulness and satisfying scales

Dependent Variable		Sum of Squares	df	Mean Square	F	Sig.
Usefulness Rating Scale	Between Groups	5.525	2	2.763	14.000	0.001[1]
	Within Groups	2.368	12	0.197		
	Total	7.893	14			
Satisfying Rating Scale	Between Groups	9.975	2	4.988	17.603	0.000[1]
	Within Groups	3.400	12	0.283		
	Total	13.375	14			

[1]At least one value is significant different at the 0.05 level.

Table E.26: Tukey HSD analysis - – usefulness and satisfying scales

Dependent Variable	(I) Inceptor Coupling Configuration	(J) Inceptor Coupling Configuration	Mean Difference (I-J)	Std. Error	Sig.
Usefulness Rating Scale	Config. 1 BENCH	Config. 3 PUSH	-1.360[1]	0.281	0.001
		Config. 2 AUTO	-1.200[1]	0.281	0.003
	Config. 2 AUTO	Config. 1 BENCH	1.200[1]	0.281	0.003
		Config. 3 PUSH	-0.160	0.281	0.839
	Config. 3 PUSH	Config. 1 BENCH	1.360[1]	0.281	0.001
		Config. 2 AUTO	0.160	0.281	0.839
Satisfying Rating Scale	Config. 1 BENCH	Config. 3 PUSH	-1.950[1]	0.337	0.000
		Config. 2 AUTO	-1.350[1]	0.337	0.005
	Config. 2 AUTO	Config. 1 BENCH	1.350[1]	0.337	0.000
		Config. 3 PUSH	-0.600	0.337	0.217
	Config. 3 PUSH	Config. 1 BENCH	1.950[1]	0.337	0.005
		Config. 2 AUTO	0.600	0.337	0.217

[1]The mean differences are significant at the 0.05 level.

Interview

Table E.27: Comments to question 1 of the interview

Configuration	Pilot	Comments
Config. 1	Pilot A	Interferences in control at low level flight can be catastrophic if the configuration 1 is selected. The attentiveness about the inappropriate input of the trainee pilot by the FIs was high in the simulator (FIs were expecting the error), which was insufficient to compensate the helicopter oscillations.
	Pilot B	No comment.
	Pilot G	This configuration exposes the lack of FI's control authority, and an alternative to it is desirable.
	Pilot H	If a pilot freezes on control, it is a very difficult for the FI to overcome the trainee pilot. The helicopter controllability is severely affected, because the FI is no longer able to control the helicopter.
	Pilot I	The difficulties to takeover control using the configuration 1 are realistic and unpleasant.
Config. 2	Pilot A	Automatic decoupling is more intuitive and presents a faster aircraft response time (reaction to the corrective action).
	Pilot B	The brief force fight condition is unpleasant, but it is not as bad as configuration 0. Minor overcontrol can occur.
	Pilot G	Full flight control authority to the FI is desirable, so it is better than the virtual rigid coupling (configuration 1).
	Pilot H	A good alternative to configuration 1. The stick shake may cause a delay in the recovery task.
	Pilot I	Automatic decoupling represents a more natural reaction of the pilots to correct inappropriate inputs. It has its own importance, depending on the scenario. This configuration is quicker and useful in a number of conditions.
Config. 3	Pilot A	The pushbutton option showed to be reliable in case of delayed reaction or high workload. This configuration is a good feature to be available in future designs. However, the constant application of trim release (another button in the cyclic sidestick) with the same finger used to decouple inceptors (the thumb) is an issue. Preferably, the manual decoupling shall occur before the corrective action of the FI, to avoid force fight between the pilots and helicopter oscillations. However, it is mentally demanding to the FI to judge this moment.
	Pilot B	Manual decoupling is reliable, predictable, not an unpleasant feature, not leading to overcontrol, simple and easy to use.
	Pilot G	Manual decoupling is fast and effective.
	Pilot H	This configuration is the clean, fast, and induced minor oscillations.
	Pilot I	In confined area, the configuration 1 leads to less overcontrol than configuration 2, so pushbutton is preferred only in this scenario. It is not always intuitive to use it.

Table E.28: Comments to question 2 of the interview

Configuration	Pilot	Comments
Config. 1	Pilot A	The monitoring/supervision technique of the FI involves the assessment of the inputs of the trainee pilot. The electronic inceptor coupling is helping to accomplish this task.
	Pilot B	The inceptor coupling seems ok.
	Pilot G	The ability to monitor the inputs was affected by the lack of familiarization with the inceptor type (sidesticks). However, it seems to be good enough.
	Pilot H	The sidestick control travel is lower than the conventional inceptors. So, the muscular feedback to pilots is different compared to the long cyclic poles. It is a known problem of the sidesticks, and it can affect the information perceived by the instructors.
	Pilot I	The inceptor gives the impression that is the same as mechanically coupled.

Table E.29: Comments to question 3 of the interview

Configuration	Pilot	Comments
Config. 2	Pilot A	It is more intuitive than the pushbutton. The inceptor decoupling is useful and positive to the proposed task.
	Pilot B	Automatic decoupling is triggered by a force fight condition, which is not a requirement for the manual decoupling. It can be somehow predictable, but cannot be avoided. Inputs after decoupling seem to be less precise (minor overcontrol).
	Pilot G	The task can be accomplished in general without unsafe conditions.
	Pilot H	A force fight condition is required to trigger the decoupling, so it can be used in time-critical conditions.
	Pilot I	Very useful to be used eventually. It can be activated according to the mission. FHS is an example.
Config. 3	Pilot A	It is unlikely that the pilot would fly with thumb on the button for the whole flight (e.g., NVG, or NOE, low level flight can last at least 30 min). The inceptor decoupling is useful and positive to the proposed task.
	Pilot B	Manual decoupling is nearly perfect. It works well, and would be used in training with high level of confidence. Desirable for helicopters in general. It opens up a new possibility to execute the task of takeover control. It is up to the pilot to use this resource. Since it seems to be very useful, it is likely that the pilot uses it eventually (when the situation requires the usage).
	Pilot G	Same comments as question number 1.
	Pilot H	Considering the full spectrum of the inceptor application, it is highly desirable to have the decoupling with the button. By pressing the pushbutton, the pilots just do it, and the response is quick and efficient.
	Pilot I	It is very useful to be used eventually. It can be activated according to the mission. ACT/FHS is an example.

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