HELICOPTER AUGMENTED CONTROL LAWS FOR SHIP DECK LANDING: HACLAS ONERA/DLR JOINT TEAM

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Abstract
Different types of control laws are implemented, tested and compared for maritime operations particularly ship deck landing maneuvers at the flight simulation facilities at both DLR (German Aerospace Center) and ONERA (The French Aerospace Lab). At DLR, "classical" cyclic and collective stick flight controls were used during the piloted simulator trials while active side-sticks were operated at ONERA. A joint maritime scenario for ship deck landing in the simulation environments of both institutes is presented. Test methodologies and assessment techniques to evaluate the ship deck landings are harmonized based on different criteria such as quantitative measures and handling qualities (HQ) ratings in order to analyze the developed control laws. Simulation results based on pilot studies for an EC135 in the DLR simulator and an EC225 at ONERA are presented.

NOTATION

Symbols

$\Delta\phi$, $\Delta\theta$, $\Delta\psi$	Attitude error in degrees
ΔV_x, ΔV_y, ΔV_z	Velocity error in m/s
V_{IAS}	Indicated airspeed in m/s
Δx, Δy	Position error in m

Abbreviations

ACAH	Attitude Command Attitude Hold
ACP	Airload Computation Point
ACT/FHS	Active Control Technology/ Flying Helicopter Simulator
ACVH	Attitude Command Velocity Hold
ACVsH	Attitude Command Ship Velocity Hold
ADS-33	US Army Aeronautical Design Standard
AVES	Air Vehicle Simulator
CFD	Computational Fluid Dynamics
DIPES	Deck Interface Pilot Effort Scale
DLP	Digital Light Processing
DLR	German Aerospace Center
DOF	Degrees of Freedom
DVE	Degraded Visual Environment
FoV	Field of View
HH	Height Hold
HOSTAC	Helicopter Operations from Ships other than Aircraft Carriers
HQR	Handling Quality Ratings
JONSWAP	Joint North Sea Wave Project
LED	Light-Emitting Diode
MSS	Maritime Systems Simulator
MTE	Mission Task Element
PALS	Pilot Assisted Landing System
PH	Position Hold
RCAH	Rate Command Attitude Hold
RCDH	Rate Command Direction Hold
RTIG	Real Time Image Generator
RTOS	Real Time Operating System
RTRC	Relative Translational Rate Command
SCONE	Systematic Characterization Of the Naval Research
SDK	Software Development Kit
SHOL	Ship Helicopter Operational Limits
TC	Turn Coordination
TRC	Translational Rate Command

1. INTRODUCTION

Maritime helicopter operations often create high stress levels and increased pilot workload because of not only the complexity of the maritime manoeuvres themselves but also the intricate aerodynamic environment, high sea states and high ship motions. Such conditions, turbulent ship air-wake, poor visibility and atmospheric disturbances can lead to the limitation of operational capabilities of the rotorcraft. In the framework of the DLR (German Aerospace Center)/ONERA (French Aerospace Lab) cooperation, one of the objectives of the Smart Rotorcraft Research Field 3 (RF3) is to develop and evaluate the enabling technologies for "easy flying" helicopters. This objective can be reached using augmented control laws. Such control laws are particularly valuable for rotorcraft ship deck operations, which are some of the most demanding of all rotorcraft piloting tasks [1]. Assessing different levels of augmentation and determining flight control law requirements for such complex maneuvers can help to improve safety, reduce pilot effort and workload and increase the helicopter-ship operational envelope [2].

There also exist control methodologies in literature in order to improve the overall performance of the ship deck landing missions. The implementation and pilot evaluation studies of different augmented response types such as Attitude Command Attitude Hold (ACAH), Acceleration Command velocity Hold (ACVH), Translational Rate Command Position Hold (TRC/PH) and amplitude dependent ACVH/TRC hybrid response types based on diverse control methodologies like Nonlinear Dynamic Inversion or model-following architecture were presented in [3] and [4]. The current collaboration allows evaluating and comparing ship deck landing control laws for different helicopter types (e.g. EC135 at the DLR vs EC225 at the ONERA) and leading further investigation in this field.

The structure of the paper is the following: Section 1 provides an overall introduction of the challenges faced during maritime maneuvers and the state of the art of the development of control laws. Section 2 describes the objectives of project HACLAS. Section 3 provides the details of the simulation facilities and the maritime simulation environment used for the development of helicopter augmented control laws for the shipboard operations at both DLR and ONERA. The recent developments on the helicopter ship deck control laws at both the institutes are presented in Section 4. Section 5 describes the overall scenario for the pilot studies that have been conducted in both the simulation facilities at

DLR and ONERA to evaluate and compare implemented basic and advanced control modes for shipboard operations. In Section 6, the simulation results are discussed demonstrating the investigation and the comparison of advanced control laws implemented at DLR and ONERA based on piloted simulation studies. The paper also discusses additional benefits of using adapted stick dynamics and haptic cueing for better efficiency and reduced workload.

2. PROJECT HACLAS

DLR and ONERA are working together to bundle their experience in flight controls and maritime operations. This is currently done through a common and cooperative project called HACLAS.

The goal of the joint team is to implement, test and compare different types of control laws for maritime operations especially ship deck landing maneuvers and to deliver requirements regarding the control law characteristics. The main objectives of this project are:

1. Prepare a joint scenario for ship deck landing in the simulation environments of DLR and ONERA (including ship motions, ship air wake etc.).
2. Harmonize test methodologies and assessment techniques. Different criteria could be defined and used such as handling qualities (HQ) ratings, safety criteria, impact on Ship-Helicopter Operational Limits (SHOL), etc. [5].
3. Analyze different flight control laws such as Rate Command Attitude Hold (RCAH), Attitude Command Attitude Hold (ACAH), Translational Rate Command (TRC). Optionally implement and analyze advanced control laws such as relative TRC, transition between control laws etc.

3. SIMULATION ENVIRONMENT

The following section describes in detail the simulation environments used for the current pilot studies to investigate the augmented control laws implemented specifically for ship landings at both institutes: DLR and ONERA.

3.1. The Flight Simulation Facility at DLR

The pilot assessments were conducted at the Air Vehicle Simulator (AVES) located at DLR, Braunschweig as shown in Fig. 1. Two interchangable cockpits can be operated on a full-sized six degrees of freedom

(DOF) hexapod motion-based platform or a fixed-based platform using a roll-on/roll off (RoRo) system. The cockpit of DLR's research helicopter Active Control Technology/ Flying Helicopter Simulator (ACT/FHS) is represented, which is a highly modified EC135. The cockpit is incorporated with additional research measurement equipment such as side-stick controls and experimental displays with touchscreen capability on the pilot side.

3.2. Visual Environment in AVES

The visual projection system contains in total 15 DLP-based LED projectors, each with a native resolution of 1920x1200 pixels. A vertical field of view (FoV) of -55° to 40° and a horizontal FoV of -120° to 120°is displayed in the dome shaped design of the simulator. The software architecture is based on a distributed software design concept where several software modules can run either on a single computer connected via Ethernet, or run together on multiple computers.

For the image generation software, DLR's in-house developed PC-based image generation system that uses OpenGL based render engine, Real Time Image Generator (RTIG) is used. This object-oriented software is adaptable to extend functionalities or integrate new features according to the research requirement. Several visual features can be integrated varying from simple 3D dynamic objects up to special visual features of diverse environmental effects like fog, brownout and wave and water effects.

3.3. Ship Dynamics and Weather Simulation in AVES

For the helicopter deck landing study at DLR, the maritime environment comprised of a detailed 3D graphical model of the German Navy F124 'Sachsen class' frigate shown in Fig. 2, a vehicle simulation model to represent the ship dynamics and a wave and water effects and weather simulation.

The in-house enhanced traffic server software VehicleControl is used for simulating the ship dynamics. It can be used to model the dynamics of vehicles using simple motion equations, trajectory following algorithms or by using complex MATLAB/Simulink models. The vehicle dynamics can be computed synchronously to other simulation models such as the helicopter flight model. For the current study, a MATLAB/Simulink model was used, which was created using the Maritime Systems Simulator (MSS) library [6]. Currently, it simulates the dynamics of a S175 ship model and uses the Joint North Sea Wave Project (JONSWAP) wave spectrum [7] for the wave

Figure 1 Air Vehicle Simulator (AVES) at DLR

generation. Since the model uses a separate wave generation engine, the ship movement is not synchronized with the waves shown in the visualization. The Sundog Triton Ocean Software Development Kit (SDK) is implemented in the RTIG software in AVES for representing a water and wave visualisation. The waves are generated using the JONSWAP wave program via the SDK. The weather simulation and 3D cloud simulation are generated using the Sundog Silverlining SDK.

3.4. Helicopter Flight Model in AVES

DLR's nonlinear real-time helicopter modeling program HeliWorX has been used at AVES to model the ACT/FHS. It is based on the helicopter modeling program SIMH [8] and each helicopter model consists of a set of modular components (fuselage, stabilizers, main rotor, etc.). The main rotor blades are considered as rigid blades and each main rotor blade is divided into 10 blade segments. The Pitt & Peters dynamic inflow model is used [9].

Moreover, the nonlinear helicopter model in HeliWorX comprises of additional features such as an interface to superimpose additional velocities from turbulent ship airwakes on 44 Airload Computational Points (ACPs) at the helicopter model (Fig. 3). These wind fields have been generated using High-fidelity Computational Fluid Dynamics (CFD) [10]. The unsteady airwake data is used as a lookup table within the helicopter simulation, which is looped in time to enable continuous simulation above the ship deck.

3.5. The Flight Simulation Facility at ONERA

In parallel, the piloted simulations to evaluate ship deck landings were also performed at the PycsHel

Figure 2 DLR's simulator - Cockpit point of view during maritime simulation

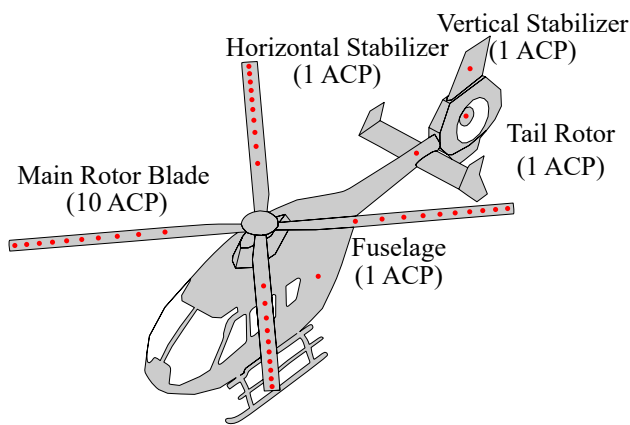**Figure 4** ONERA's simulator - Cockpit point of view during maritime simulation

Figure 3 Distribution of Airload Computation Points (ACPs) in HeliWorX

simulation bench located at ONERA center, Salon de Provence, as shown in Fig. 4.

The real-time core data-centric structure based on DDS (OpenSpliceDDS Community Version by Vortex) is built as a mutimodel architecture allowing the integration of multiple language models (MATLAB/SIMULINK, C++, FORTRAN, etc.).

3.6. Visual Environment in PycsHel

ONERA's PycsHel is a prototyping simulation bench dedicated to Vertical Take-Off and Landing Systems. The half cave video projection room offers a 270° horizontal field of view plus the ground display. Cockpit displays are three tactile screens, not representative of existing on-board systems but all information required to perform elementary missions are present. They are built with OpenSceneGraph and can be customized according to the needs. Of-

fering a dual configuration, flight controls are based on four active side-sticks, manufactured by Wittenstein for the cyclics, and Safran Electronics and Defense for the collectives.

Visuals are based on the Open-source 3D toolkit OpenSceneGraph, orthophotographic and height-field based terrains fuelled by real-world geomatic data. Four new laser-based projectors from Barco (F80) have been integrated in the simulation bench in 2021. This projection system has native WQXGA resolution (2560x1600) and up to 4K using pixel shift technics. It also allows stereoscopic or dual pilot point of view capabilities.

3.7. Ship Dynamics and Weather Simulation in PycsHel

A 3D model of a Lafayette frigate is integrated in the visual environment. Sea and atmospheric representations are performed through SunDog Triton Silverlining software, enabling real 3D waves for any Beaufort scale and ship wake. Ship movements are generated using a model, identified on the basis of experimental data on the deck movements of a Lafayette-class frigate.

3.8. Helicopter Flight Model in PycsHel

The flight mechanic code used in this project is the HOST code from Airbus Helicopters, modelling an EC225 helicopter. HOST code integrates a ship air-wake model developed by ONERA in 1997 and based on wind tunnel measurement campaigns on a Lafayette frigate model as shown in Fig. 5. The frigate air-wake model and its implementation in

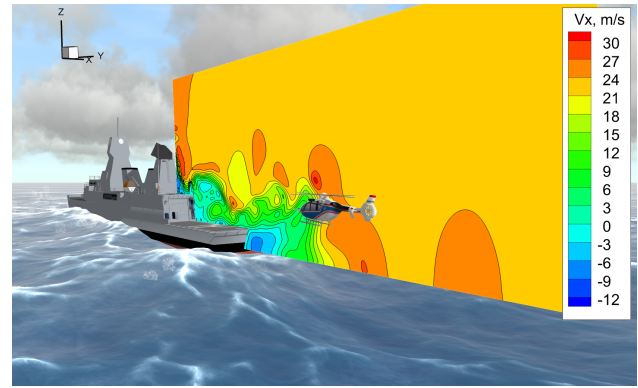**Figure 5** Ship air-wake measurements at IMFL wind tunnel facilities

Figure 6 F-124 class frigate with turbulent air-wake.

the HOST code are detailed in the following conference paper [11].

4. TECHNICAL DEVELOPMENTS

The technical developments performed at DLR and ONERA joint team under the project HACLAS are described in the following section.

4.1. Frigate Air-wake at DLR

A turbulent air-wake behind a F124 Sachsen Frigate shown in Fig. 6 is generated and implemented in the non-linear model of ACT/FHS, HeliWorX. This model is used for real-time simulations in the AVES. The HeliWorX model features an interface to superimpose velocities from turbulent ship air-wakes. The unsteady air-wake data is used as a lookup table within the helicopter simulation, which is looped in time to enable continuous simulation above the ship deck. In addition, temporal blending is performed at each time loop for smooth transition. The spatial dimension ($120 \times 80 \times 40$ m), the spatial discretization ($\Delta x = 0.3$ m) and the temporal discretization ($\Delta t = 0.04$ s) of the unsteady air-wake cause a memory consumption of approximately 60GB.

4.2. Advanced Flight Control Modes at DLR

Another development from DLR side is the implementation of advanced control modes to make the landing task easier for the pilots. Three basic command types:

- Attitude Command Attitude Hold (ACAH)
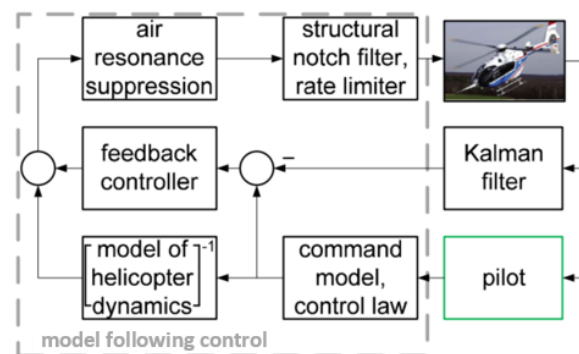- Rate Command Attitude Hold (RCAH)
- Translational Rate Command (TRC)

Figure 7 Schematic of the model-following control system

and three advanced command types:

- Attitude Command Velocity Hold (ACVH)
- Relative Translational Rate Command (RTRC)
- Ship-based Attitude Command Velocity Hold (ACVsH)

were implemented [12]. The control modes are implemented in a pre-established and flight-tested model following control system which imposes the desired command model dynamics on the controlled helicopter [13]. This model-following control system has three major components: a command model, a feed-forward controller and a decoupled cascaded feedback controller as shown in Fig. 7. The command model generates the reference signals for the desired helicopter motion. Various command types combined with various hold functions are implemented in the command model.

The feed-forward controller provides basic response decoupling and improves the response quickness. A 11-DoF helicopter dynamic model which is derived by system identification in time domain is the base for the feed-forward controller [14].
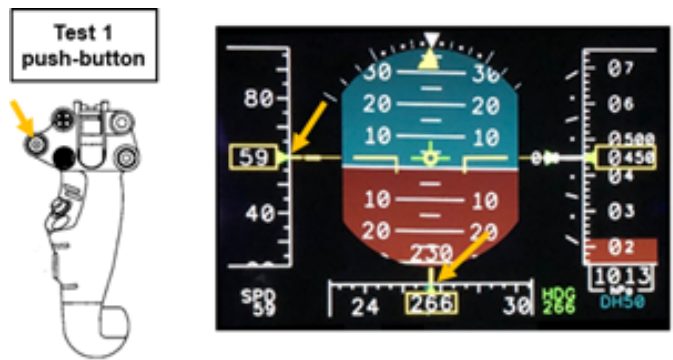
(a) Activation of the ship landing mode: The current speed and course are stored as reference and followed by the FCS
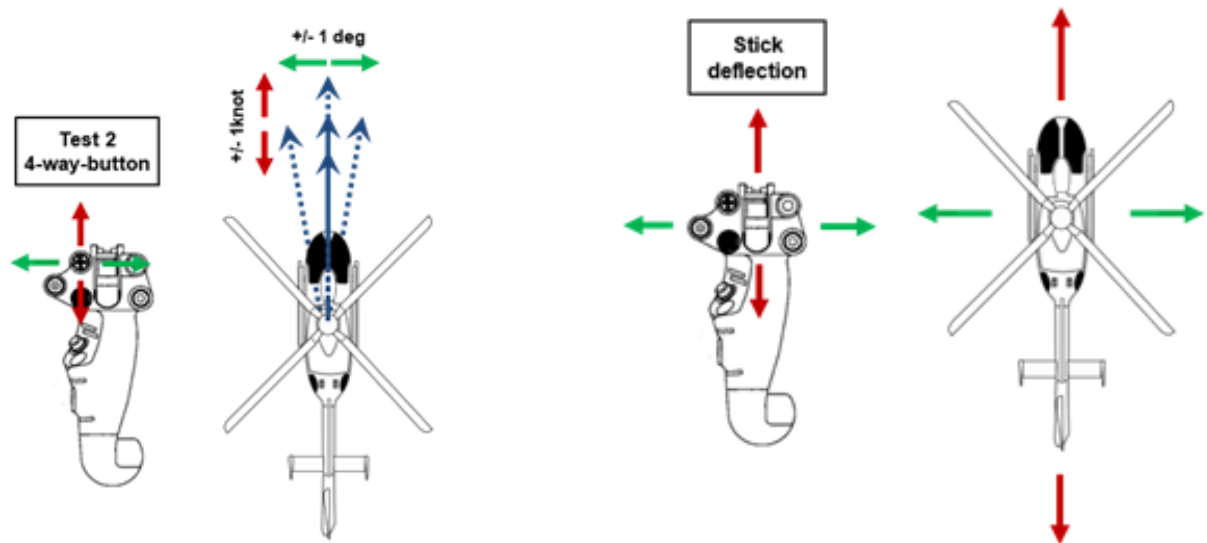
(b) Fine adjustments to the reference ground speed and heading can be made continuously with the 4-way Test 2 button to follow the ship's trajectory

(c) Longitudinal and lateral shifting towards the landing deck is performed by the ACAH by means of stick deflection. The reference ground speed is restored by the FCS when the stick is released

**Figure 8** ACVH control mode activation and handling

The feedback controller compensates differences between commanded and measured values due to modeling deficiencies and other disturbances. It also establishes the desired hold types, e.g. attitude hold. Three classical command types, namely Attitude Command Attitude Hold (ACAH), Rate Command Attitude Hold (RCAH) and Translational Rate Command (TRC) were implemented in the AVES. The first advanced control mode, Attitude Command Velocity Hold (ACVH) combines a trajectory hold (ground speed and heading) function when the cyclic stick is released with an attitude command mode when the stick is moved as shown in Fig. 9. The pilot can also adjust the heading and speed of the helicopter using the 4-way stick button on the cyclic stick. The key feature of this mode

is that no communication is required between the ship and the helicopter. Such a mode could be useful in for example for EMCON (Emission Control) missions where no communication with the ship is allowed. The vertical mode provides a classical rate command / altitude hold. Another advanced control mode, Relative Translational Rate Command (RTRC) has been developed and implemented in the ACT/FHS flight control system at DLR. When the mode is activated, the helicopter velocity is matched to the current ship velocity when the cyclic stick is released and can be used as a standard TRC mode when the stick is moved.

The third advanced mode named ACVsH also involves communication with ship. In this mode, upon activation the helicopter holds the ground speed
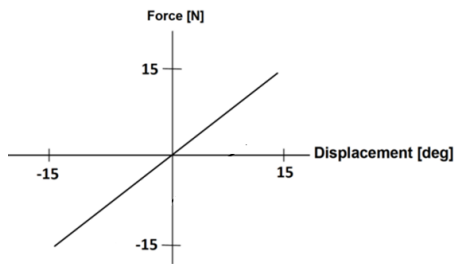
(a) Force/displacement curve of 1N/deg
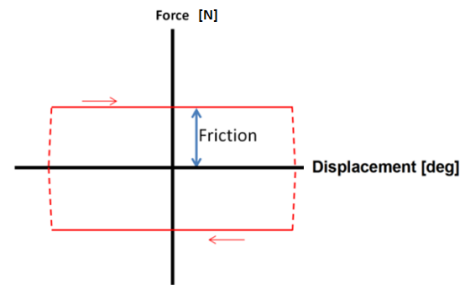
(b) Friction used as force/displacement curve

Figure 9 Classical Force/displacement curves

and heading of the ship when the stick is not moving and is a standard attitude command mode when the stick is moved. Hence, on activation the ship speed and heading is matched and the pilot can also adjust the heading and speed of the helicopter using the 4-way stick button on the cyclic stick.

4.3. Simulator Trials Analysis Tools at DLR

For the simulator trials performed in DLR's AVES, an overall evaluation toolchain for assessing the helicopter ship deck landings was implemented [15]. The toolchain evaluates various touchdown conditions like position, velocity and attitude errors between the ship deck and the helicopter along with additional evaluation parameters for the entire approach such as levels of control activity: amplitude and frequency, lateral track: distance about the ship axis, position and track error (x and y) and heading variations during the whole flight trajectory. For a subjective assessment, qualitative pilot ratings using different rating scales namely Cooper-Harper rating scale and DIPES (Deck Interface Pilot Effort Scale) were recorded during the pilot study [16] and [17].

4.4. ONERA Developments

From ONERA side, the following basic control modes: Attitude Command Attitude Hold (ACAH), Rate Command Attitude Hold (RCAH), Translational Rate Command (TRC), HH (Height Hold = Heave TRC) and AcVH (Acceleration Command, Velocity Hold) were implemented in ONERA'S PycsHel simulator and tuned for an EC225 helicopter model. While not evaluated yet, a relative TRC (based on the DLR approach) has been also developed and implemented in PycsHel.

At DLR, "classical" cyclic and collective stick flight controls were used during these trials while active side-stick units were operated at ONERA. Dur-

ing preliminary trials, it was observed that, with TRC, pressing the trim button can induce very slight movements of the stick, and thus a transient speed set point. To avoid this, the nominal effort/stick position law (1 Newton/deg), as shown in Fig. 9a, has been replaced by friction (2 Newtons) on the longitudinal axis (see Fig. 9b) while the classical force/displacement curve was maintained on the lateral axis. This modification allows to place the stick at a given position (i.e. given target speed), and release it without any unintentional move as the trim button has no more to be pressed.

Moreover, detents were implemented on both cyclic and collective sticks to indicate specific speeds to the pilot. A detent simulates a ball and groove feature where a ball and spring are moved over a surface with a groove in it (e.g. an aircraft throttle).

The detent parameters that can be set are the center position, width, height, dead-band (located around the center) and the scale factor (affecting the sharpness of the detent).

One detent was placed at the neutral position of collective, enabling the precise recognition of the null vertical speed by the pilot. In addition, a glide slope guidance function sets a detent at the collective position corresponding to the required vertical speed to follow a predefined glide path angle. On cyclic, different possibilities are offered. Positioning the detent at the neutral stick position enables the recognition of null angular rate commands in RCAH, null attitudes in ACAH, or null velocity in TRC depending on the law engaged (RCAH, ACAH or TRC). In addition, ship speed can also be indicated by a detent positioned at the associated longitudinal cyclic stick displacement. This last feature can be considered as a kind of relative TRC, as the pilot is then able to position its cyclic around this detent, and to control the horizontal speed around the ship speed. The use of haptic cueing showed real benefits and the possibility to increase the efficiency of augmented flight control laws.

5. PILOTED SIMULATION

During the pilot studies at DLR and ONERA, the pilots performed multiple ship deck landings on a frigate class ship in order to evaluate the implemented control modes. The complete details about the piloted simulation are described in the following section.

5.1. Pilots and Pilot Task

A total of five helicopter pilots with different levels of experience as described in Tab. 1 participated in the piloted simulation study. Pilot 1 and Pilot 2 are doing research in the area of scientific flight testing and both of them are experienced with subjective pilot rating methods. Pilot 1 is qualified as an experimental test pilot, Pilot 2 and Pilot 5 are doing research and their experience is considered highly valuable for the evaluation. Pilot 3 is a military pilot from the German Navy and is familiar with helicopter ship deck landings of Lynx helicopters on the considered F-124 class frigate. Pilot 4 is a pilot from the German police and Pilot 5 is a French navy pilot. Both Pilot 4 and Pilot 5 are familiar with helicopter ship deck landings.

The task performed during the simulator trials at DLR was based on the standard port lateral approach as defined in the Helicopter Operations from Ships other than Aircraft Carriers (HOSTAC) as shown in Fig. 10 [18]. Standard Port Lateral Approaches are usually performed in the direction opposite to the air-wake. However, the chosen maneuver is with an approach from the turbulent air-wake to make the task more challenging and hence more suitable for the evaluation of the control modes.

The pilots begin the task at a height 65 ft with a forward speed 20 knots approximately 600 ft behind the ship and establishes a hover alongside the deck, followed by a lateral transition maintaining the same altitude over the deck [19]. Upon detection of a quiescent period, a vertical descent followed by the landing is performed. The pilots repeated each landing using different control modes 2-3 times.

It has to be noted that, while at DLR the scenarios were started in the vicinity of the ship, simulation runs were initiated much away from the ship at ONERA, allowing the study of the entire approach. The maneuver was defined as depicted in Fig.11. Only straight-in maneuvers were performed at ONERA, defined by:

- At 4000 yards behind the ship, the helicopter is in level flight, at 60 kts, at 500 ft above sea;
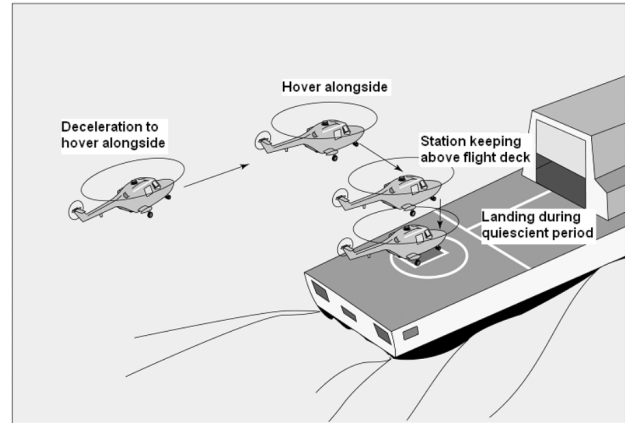

Figure 10 Deck Landing Mission Task Element [20]

- At 2550 yards behind the ship, helicopter initiates descent at constant glide (following glide slope indicator of the ship) along the trajectory.
- At ship fantail, the helicopter velocity is the ship velocity (10 kts during the trials);
- The vertical speed is adapted to maintain a constant glide slope of -3 deg.

5.2. Test Scenario and Test Configurations

During the pilot study at DLR, the deck motion simulation modelled after a German Navy F124 'Sachsen class' frigate was used. The frigate was proceeding at 10 knots in sea state 6 with the sea approaching at 30° to the bow. The frigate ship dynamic model also included a simulation of turbulent ship air-wake attached to it. A good visual environment (GVE) as shown in Fig. 2 was used for the evaluation of helicopter ship deck landings.

The major goal of the piloted evaluations was to assess and compare the performance of augmented control modes during ship deck landing maneuvers for different helicopter types at both DLR and ONERA. Therefore, the test matrix was created for very particular conditions.

For the pilot study in AVES at DLR, test points were based on five different flight control configurations (except RCAH) as provided in Tab. 2 for each individual axis. Pilots highlighted that the RCAH is clearly not adapted to this procedure as it resembles flying in direct mode. Hence due to time constraints, RCAH was not considered in the final test matrix.

During the simulator trials at ONERA, the Lafayette Frigate was following a North route at a constant speed of 10 kts. As proceeding to straight in approaches, the wind was aligned with the ship (azimuth 0 deg) with a magnitude of 10 kts. Different

Table 1 Overview of pilot experience

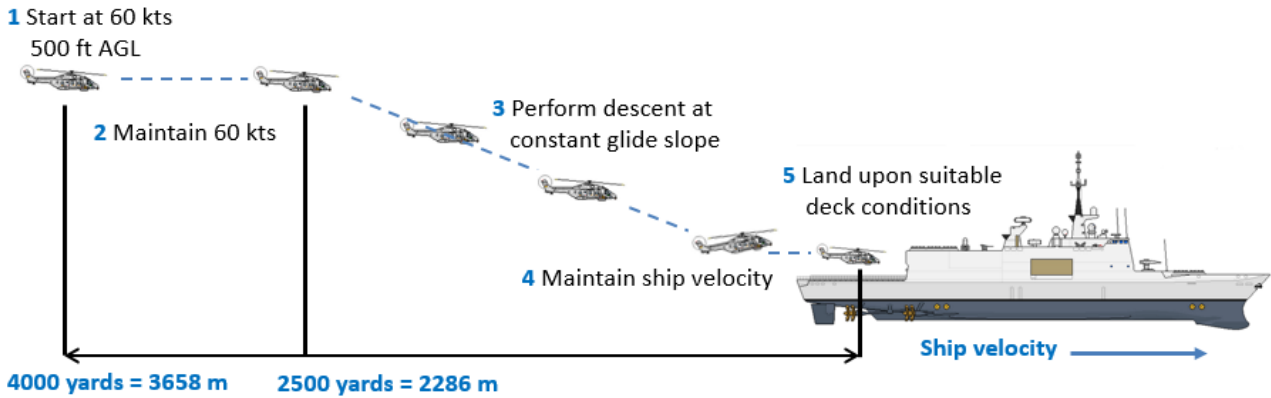|	Pilot 1	Pilot 2	Pilot 3	Pilot 4	Pilot 5
Pilot license	41 years	12 years	25 years	15 years	20 years
Experimental test pilot	Yes	No	No	No	No
Total flight hours	6700 h	1050 h	3900 h	2800 h	2200 h
Offshore flights per year	-	-	50	50	50
Proportion of offshore flights per year	0%	0%	50-75%	25-50	50-75%%
Maneuver: Ship deck landing per year	0	0	≥ 30	≤ 10	≥ 30

Figure 11 ONERA's deck landing scenario - Straight In approach

Table 2 Test configurations used at DLR

Config.	ACAH	TRC	ACVH	RTRC
Pitch	ACAH	TRC	ACVH	RTRC
Roll	ACAH	TRC	ACVH	RTRC
Yaw	RCDH	RCDH	ACVH	RCDH
Heave	HH	HH	HH	HH

Table 3 Test configurations used at ONERA

Config.	ACAH	RCAH	TRC
Pitch	ACAH	RCAH	TRC
Roll	ACAH	RCAH	TRC
Yaw	RCDH	RCDH	RCDH
Heave	HH	HH	HH

runs were based on three different flight control configurations as provided in Tab. 3

5.3. Assessment Methods

The evaluation of the implemented control laws was performed using the implemented toolchain by analyzing objective simulation data, subjective pilot ratings and the pilot feedback during the simulation. For the objective evaluation, task performance is evaluated during the approach and at the touchdown point. The implemented toolchain evaluates the touchdown conditions specifically the position error $(\Delta x, \Delta y)$, velocity error $(\Delta V_x, \Delta V_y, \Delta V_z)$ and attitude error $(\Delta \phi, \Delta \theta, \Delta \psi)$ between the ship deck and the helicopter. The quantitative mission success is determined depending on if the pilot could achieve the desired or adequate limits during landing. The desired and adequate boundaries are defined for each of the touchdown conditions based on the size

of helicopter, size of ship and the pilot feedback [12]. Along with the touchdown evaluation, the objective criteria to evaluate the entire manoeuvre such as levels of control activity: amplitude and frequency and position and track error (x and y) during the whole flight is also investigated for extra knowledge but not used as a part of evaluation.

For the subjective evaluation, pilots awarded ratings based on different rating scales namely: Cooper-Harper Handling Qualities Rating Scale (HQR) and Deck Interface Pilot Effort Scale (DIPES) after each experiment.

The Cooper-Harper rating scale was used to assess the handling qualities of the helicopter during the final phase of the landing [16]. It consists of a decision tree and ranges from ratings 1 to 10 defining the best handling qualities of an aircraft as 1 "excellent, highly desirable" and the worst handling qualities as 10 "major deficiencies". The handling qualities ratings (HQR) in the range of 1-3 represents Level 1,

in the range of 4-5 represents Level 2 and the rest Level 3 Handling Qualities. The Cooper-Harper rating scale is a highly complex scale and hence is normally used only by experimental test pilots.

DIPES was used to quantify the workload of an average fleet pilot and is designed in particular for ship deck landings [17]. Using this 5-point scale, the pilot rates the landing maneuver based on workload, performance, accuracy, and consistency. Ratings between DIPES-1 to DIPES-3 are considered as acceptable and ratings of DIPES-4 to DIPES-5 are considered as unacceptable. Moreover, each rating can be supplemented with letter suffixes explaining the cause of growing workload (e.g. 'D' for deck motion or 'V' for visual cues). The pilots were asked to give at most three additional suffixes, if needed.

6. SIMULATOR TRIAL RESULTS

In the following section, the results of the evaluation of the ship deck landing scenario and the flight control modes at DLR and ONERA are presented.

6.1. Evaluation at DLR

The simulator trials at DLR were focused to evaluate the ship deck landing scenario and to evaluate and compare the flight control modes for their suitability for ship deck landing missions. All aforementioned pilots participated in the simulation trials at the AVES. Each pilot performed each test independent from the other pilots. The simulation results are focused on Pilot 3, Pilot 4 and Pilot 5 as they had experience with maritime missions.

The objective assessment majorly involved the evaluation of the touchdown conditions. In addition, the entire maneuver was also analysed to have a deeper knowledge of the approach phase. Three metrics; position offset, velocity error, and attitude error at the touchdown point were evaluated. Fig. 12 shows the touchdown positions of the helicopter relative to the deck center by the three maritime pilots for different control configurations. Due to time constraints, Pilot 3 was not able to perform a landing using ACVsH command type. The figure demonstrates the pilots could achieve a desired or at least adequate performance with almost all the command types. Fig. 13 illustrates the position of the helicopter relative to the deck center throughout the approach and during the landing phase using ACAH and ACVH control configuration. It can be seen from the landing phase in the trajectory and was also remarked by the pilots that it was much simpler to perform the landing in the ship air wake using ACVH
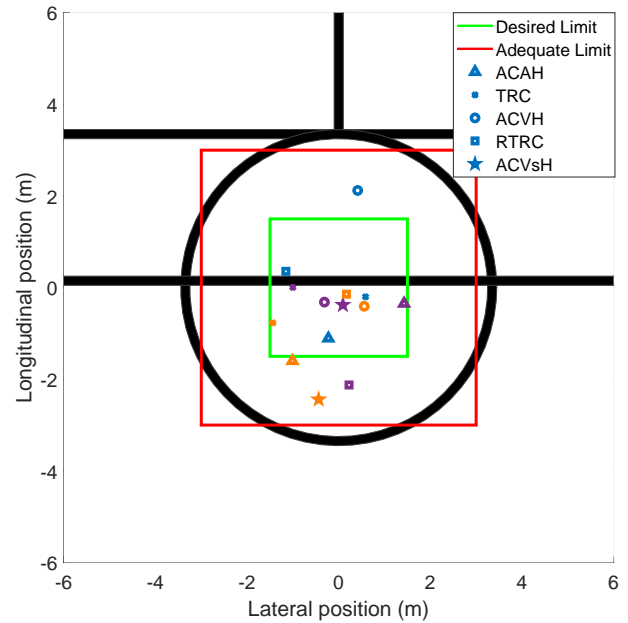

Figure 12 Landing positions relative to deck using different control configurations (Blue: Pilot 3, Purple: Pilot 4 and Orange: Pilot 5)

command type than the classical ACAH approach.

The level of control activity for performing the maneuver is also considered as a significant metric to be studied. Fig. 14 illustrates the pilot control inputs for the approach and landing phase for ACAH and ACVH control modes by Pilot 5. Lesser pilot activity was observed with ACVH mode when compared to ACAH mode. It can be also be observed that the pilots had to use more effort during the landing phase (towards the end of the flight) in comparison to the approach phase. This behaviour was observed for all control modes. This behavior is expected as the pilot has to make adjustments against the drift caused by turbulence.

For the objective assessment, the pilots went through a set of questionnaires based on different rating scales namely DIPES and HQR after each experiment respectively. For awarding Cooper-Harper Handing Qualities Ratings, the focus remained on the landing phase where as for other scales whole maneuver was addressed.

It should be highlighted that the HQR ratings were only awarded by Pilot 1, Pilot 2 and Pilot 5, because of the fact that the HQR is a relatively complicated scale. Fig. 15 shows that the pilots could achieve Level 2 or Level 1 (for advanced command types) Cooper-Harper HQRs which depicts that they achieved desired or adequate performance with a moderate compensation. It can be observed from the Fig. 15 that there was a improvement in the
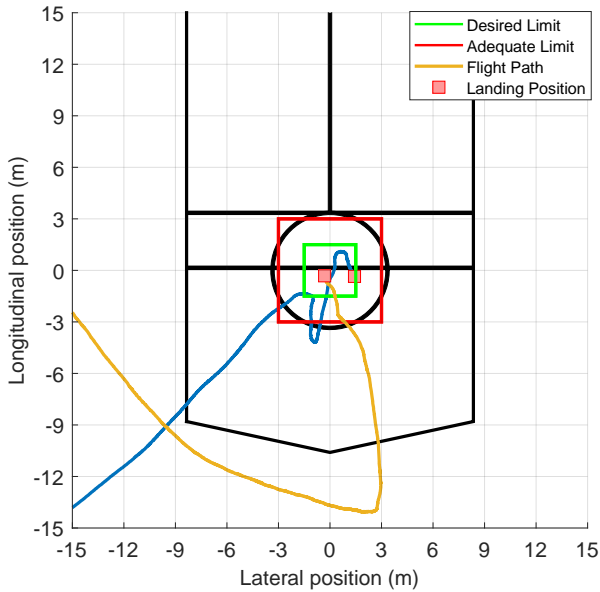
Figure 13 Helicopter position relative to landing position performed by Pilot 4 (Blue: ACAH and Yellow: ACVH)

Figure 14 Time Histories of pilot control activity throughout ACAH and ACVH approach by Pilot 5

ratings from Level 2 to Level 1 when using the advanced command types.

Fig. 16 depicts the DIPES ratings awarded by all five pilots for ship deck landings performed using all the command types. The figure demonstrates the DIPES ratings to be 'acceptable' for most of the advanced command types (TRC, RTRC and ACVsH) for almost all the pilots whereas the pilots provided higher ratings for the basic command types (ACAH and ACVH). The ratings illustrate that using the advanced command types the task became acceptable. The DIPES ratings highlighted most clearly the benefits of the RTRC mode, contrary to the ACAH (also ACVH by Pilot 4) mode, which was deemed 'unacceptable' by some of the pilots. Along with the DIPES ratings, the pilots can also describe the cause of the increased workload by providing one or more suffixes. In this study, nearly all the pilots remarked that the deck motion (D) and air wake turbulence (T) were the major causes of increased workload and made the overall task more challenging. Apart from deck motion (D) and turbulence (T), lateral positioning (L), and height control (H) were some other factors stated by the pilots for increased workload.

It should also be noted that even if some of the landings with basic command types displayed better task performance, it actually took higher pilot workload to achieve such accuracy. Besides that the higher ratings by some pilots could be impacted by not only the task being demanding but can also var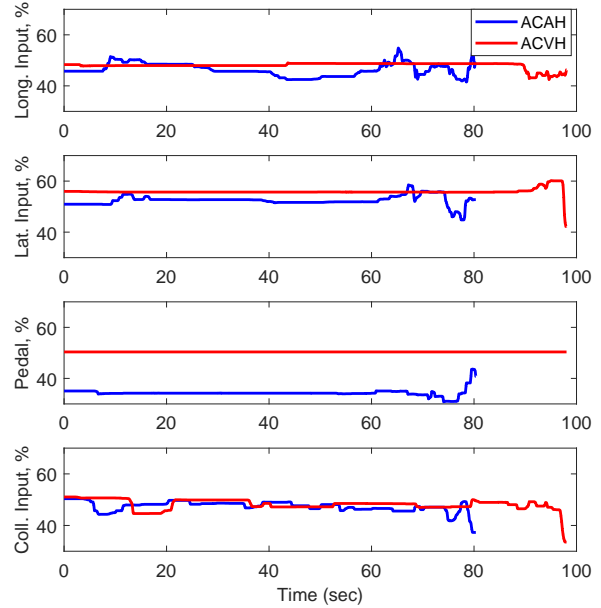y depending on the level and type of experience of the evaluation pilot as described in Tab. 1. It can be noted that the tests were performed by limited number of pilots, although according to [21] three pilots seems to be bare minimum with four likely to lead to a more reliable result.

Some of the pilots experienced a higher workload with ACVH mode, because they were not habitual using the 4-way test button to adjust the speed and heading instead of classical control inputs. However, some of them experienced a relatively higher overall workload with TRC mode specially during the approach. This is because they had to give large control inputs because usually TRC is generally used for final precision during landing whereas it was also used for the approach phase in the current study.

6.2. Evaluation at ONERA

ONERA simulator trials were performed by Pilot 5, and led to a classification of the basic control modes based on the pilot subjective feedback. Thus, it was highlighted that the RCAH and ACAH are clearly not adapted to this procedure. RCAH was a bit better rated but still required a high workload. TRC is the most efficient with a large decrease of the workload. Contrary to the results already experienced in previous studies, RCAH was here better rated than ACAH. This can be explained by less disturbance rejection capability of the ACAH implemented in the simulator compared to the RCAH for the case of PycsHel.
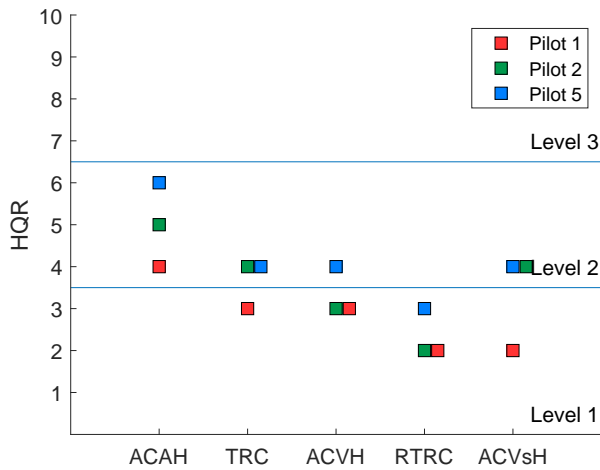
Figure 15 HQR results for ship approaches using different control modes at DLR

Figure 16 DIPES results for ship approaches using different control modes at DLR

Therefore, the pilot had more difficulties to precisely control the helicopter speed above the deck.

In Fig. 17 and Fig. 18, a comparison of pilot controls and flight parameters during the entire procedure is done, between TRC (blue line) and RCAH (red line). It is clear that the requested inputs on controls are lower with TRC, and the trajectory is much more stabilized. In this case, the pilot didn't land and fly when using the RCAH.

As previously mentioned, the force displacement curve used on the longitudinal cyclic in TRC was switched to pure friction. A deceleration from 20 kts to 10 kts (blue curve) performed with the classical force displacement curve on the longitudinal cyclic can be seen in Fig. 19. The force gradient being 1N/deg. It can be seen that at around 60s, the pilot is acting on the trim release button (red curve), generating small control variations. In Fig. 19 , the same maneuver is performed but using a 2N friction on the longitudinal, and a detent positioned to the corresponding ship velocity. The difference in terms of required pilot actions on the flight controls is clearly visible on the red curve. The pilot is able to feel the detent and place the stick immediately at the proper position to reach the ship velocity. This force law on the cyclic was considered as very well adapted. If keeping a classical force gradient curve on the lateral is adapted for straight in approaches, where only small lateral velocity corrections are needed, setting friction on the lateral axis could be beneficial for relative wind or cross deck procedures, where maintaining a lateral speed is requested.

Finally, the HH law on collective was very well appreciated, enabling a precise control of the vertical speed during the approach. In addition, the use of
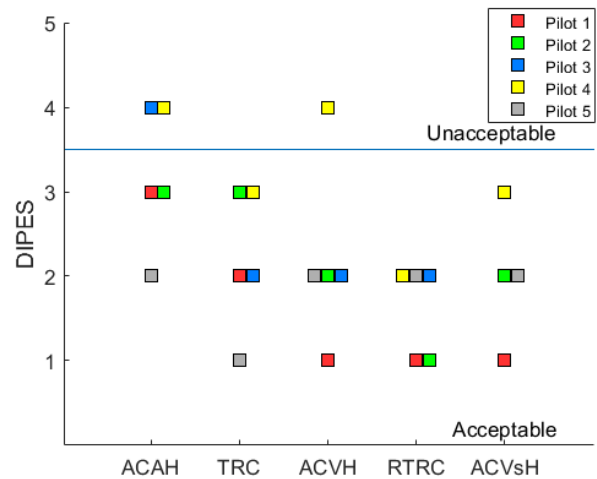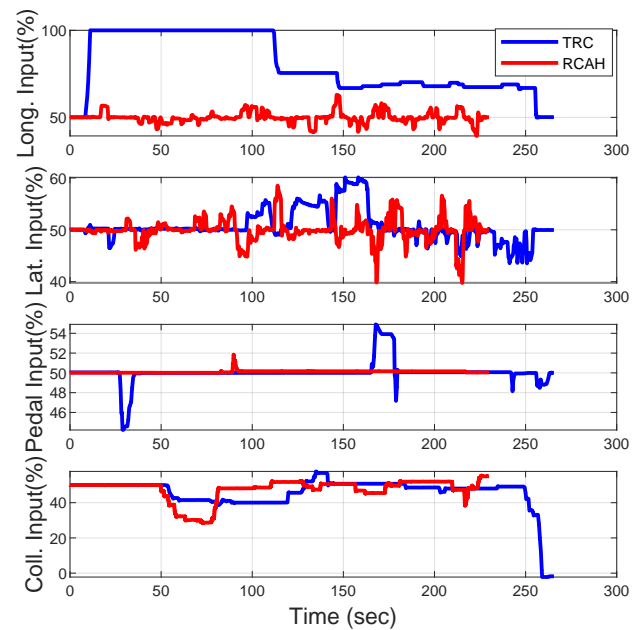

Figure 17 Comparison of pilots controls between TRC and RCAH during the procedure

detents to indicate specific vertical speeds were also very well appreciated, as also demonstrated in [22].

6.3. Pilot Feedback and Future Developments

Some requirements were expressed by the pilot after simulation trials at ONERA:

- Use of the 4-way button cyclic stick to enter set points (+- 1kt) in relation to the reference ground ship speed. Both in longitudinal and lateral.
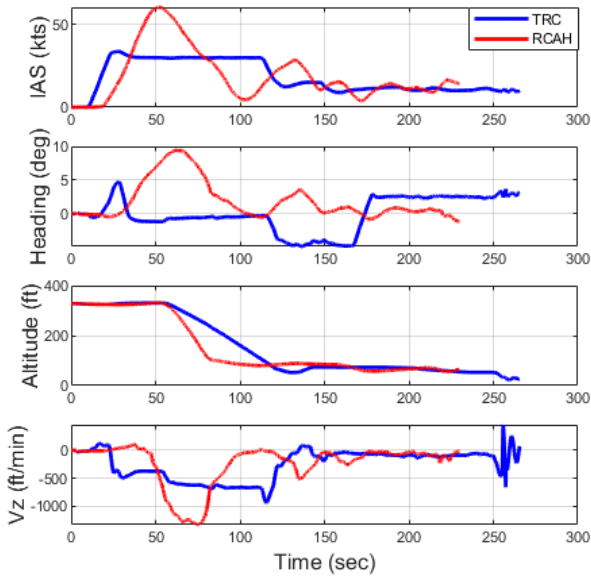
Figure 18 Comparison of flight parameters between TRC and RCAH during the procedure

- The possibility to change the course (+- 1 deg) with the 4-way button on lateral could be integrated on the collective stick.
- Possibility of a limitation of the vertical speed by the HH law before the touch down regardless of the decrease of the collective (i.e. vertical speed target).

7. CONCLUSIONS

A maritime simulation environment has been implemented in both DLR and ONERA simulators, enabling the evaluation of helicopter augmented control laws in ship deck operations. Three basic (ACAH, RCAH, TRC) and three advanced command types (ACVH, RTRC, ACVsH) were developed and tested by DLR, while ONERA focused on three basic control modes (RCAH, ACAH, TRC). Simulator trials results illustrated that even if some of the landings with basic command types displayed better task performance, it actually took higher pilot workload to achieve them. The pilot feedback indicated an extensive reduction in the workload when using the advanced command types. Among these advanced command types, Relative Translational Rate command has shown larger benefits. Finally, it has been shown that the use of active inceptors, with specific haptic cues (detents), can bring benefits in the management of augmented flight control laws.
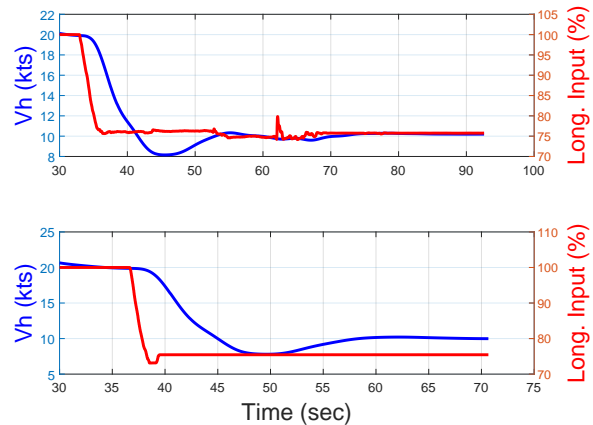

Figure 19 Comparison of a deceleration maneuver with different force displacement laws

8. ACKNOWLEDGMENTS

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