DEVELOPMENT AND EVALUATION OF HELICOPTER AUTOPILOT MODES FOR SHIP-DECK LANDING MANEUVER

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Abstract
Helicopter ship-deck landings remain a daunting task for the pilots as well as for the automatic flight control systems due to endless factors including but not limited to high sea states, highly irregular ship motion and ship air wake and turbulence. The proposed study presents classical and augmented autopilot modes in order to perform an Automatic Ship Deck Landing. The developed autopilot modes are managed by a fully automated ship deck landing controller, enabling to perform the entire maneuver for a manned or unmanned helicopter, from the stabilised level flight to the over the deck hover and final landing phase. The complete landing maneuver is split into five different phases depicting five mission task elements. In order to perform these different phases, a Transition Down auto-pilot mode has been developed, enabling to switch between appropriate autopilot modes and instructions depending on the current phase along the entire maneuver. This automatic transition down mode has been tested through off-line simulation tool integrating a maritime simulation environment. Furthermore, the maneuver has been also evaluated by two helicopter test pilots during the design process to evaluate its effectiveness in simulating a realistic operational scenario. Simulation results indicate improved task performance and improved perceived safety for the overall landing mission using the Automatic Ship Deck Landing mode.

NOTATION

Symbols

dx	Longitudinal distance deviation of helicopter from Deck Reference Point
dy	Lateral distance deviation of helicopter from Reference Point
Vx	Forward Velocity of helicopter
Vz	Vertical Velocity of helicopter

Abbreviations

ACT/FHS	Active Control Technology/ Flying Helicopter Simulator
ALT	Altitude mode
ASDL	Automatic Ship-Deck Landing mode
ASTERN	Automation of Shipboard helicopTer opERatioNs
ATT	Attitude mode
AVES	Air Vehicle Simulator
DIST	Distance between the helicopter and the Deck Reference Point
DLR	German Aerospace Center
DOF	Degrees of Freedom
DRP	Deck Reference Point
GRS	Ground Speed
GS	Glide Slope hold mode
HACLAS	Helicopter Augmented Control Laws for Ship deck landing
HDG	Heading
HOST	Helicopter Overall Simulation Tool
HRB	Horizon Reference Bar
IAS	Indicated Air Speed mode
ONERA	French Aerospace Lab
PH	Position Hold
TD	Transition Down mode
TRC	Translational Rate Command
UAV	Unmanned Aerial Vehicle
VH	Velocity Hold

1. INTRODUCTION

Helicopter ship deck landings are inherently challenging due to several factors. The dynamic and unstable environment of a moving ship, combined with adverse weather conditions, limited visual cues, and turbulent airwakes, significantly increases the difficulty of these operations for both manned and unmanned aerial vehicles (UAVs) [1] [2]. In manned missions, pilots must synchronize their maneuvers with the ship's heave movements to minimize impact energy during landing, which requires precise control and high cognitive workload [3]. Additionally, the confined landing space and six degrees of freedom motion of the ship deck further complicate the task [4].

Developing and assessing automated modes and determining auto-pilot requirements for such complex maneuvers in such difficult maritime environment can help improving safety and increase the helicopter-ship operational envelope in case of a piloted vehicle, and is even mandatory for rotary-wing UAVs [5] [6].

Moreover, automatic systems can utilize advanced sensors and algorithms to track the ship deck parameters and execute precise landing maneuvers, even under adverse conditions [7] [8]. These systems can also incorporate nature-inspired control strategies, such as optical flow theory, to achieve smooth and accurate landings [9]. By leveraging automation, the risks associated with human error are minimized, and the overall safety and efficiency of helicopter maritime operations are improved [10] [11]. Furthermore, automated landings can expand operational capabilities, allowing UAVs to perform missions in conditions that would be too hazardous for human pilots [12]

Existing studies have shown the benefits of pilot assistance systems with control augmentation featuring some of these different responses [13] [14] [15]. The integration of advanced technologies in automatic helicopter landing systems significantly enhances safety by addressing various challenges associated with manual landings. For instance, augmented reality systems improve the pilot's environmental perception, enhancing safety during landings in complex environments [16].

Even though some of the previous publications already dealt with the development of such ship-deck landing controllers, for example using the optical flow theory [9], it has to be noticed that the current study attempts to apply the controller modes in a realistic environment, integrating ship air-wake [5] and ship motions correlated to sea state, which was not always the case in previous studies.

In the framework of the ONERA (The French Aerospace Lab) / DLR (German Aerospace Center) cooperation and a previous Joint-Team named HACLAS, augmented control laws were developed and tested, showing their efficiency and benefits for rotorcraft ship deck operations, which are some of the most demanding of all rotorcraft piloting tasks [17] [18] [19]. Nevertheless, it was highlighted that introducing augmentation and automation during deck landing maneuvers could benefit to safety and of course, pilot workload reduction [20]. In addition, full automation is required for UAV ship deck operations.

Therefore, the current ONERA/DLR cooperation project called ASTERN ("Automation of Shipboard helicopTer opERatioNs") is aimed to develop and evaluate different auto-pilot modes dedicated to ship-deck landing phases. These automated modes could be managed by a fully automated ship deck landing controller, which is enabled to perform the entire maneuver for a manned or unmanned helicopter. In the framework of this project, ONERA will focus on the implementation of different autopilot modes and a complete automatic ship deck landing controller and DLR will also focus on the implementation of different automatic control modes mainly having disturbance rejection capabilities to automatize different parts of a ship deck landing maneuver. Additionally, DLR will also further investigate the implemented control laws to find a trade-off between the disturbance rejection performance and stability margins in order to cover a broader domain [21]. However, the focus of this paper lies on the implementation of the automatic ship deck landing controller and the design of the whole maneuver including approach, descend and landing.

The paper presents the development and evaluation of helicopter autopilot modes, from the initial stabilised level flight to the stabilised hover over the deck. The main focus of the paper is the development of an automatic ship-deck landing controller, integrating a deck motion estimator. The autopilot modes can be engaged by the pilot at different stages of the maneuver, therefore, the realization of the entire maneuver by an automatic controller is also considered which would even be necessary in the case of a UAV. The implemented controller is evaluated on an offline simulation tool. Simulation results demonstrate the working of the automatic ship deck landing maneuver by performing a complete approach and landing in the presence of wind and ship airwake. Furthermore, the maneuver has been also evaluated by two helicopter test pilots during the design process to evaluate its effectiveness in simulating a realistic operational scenario.

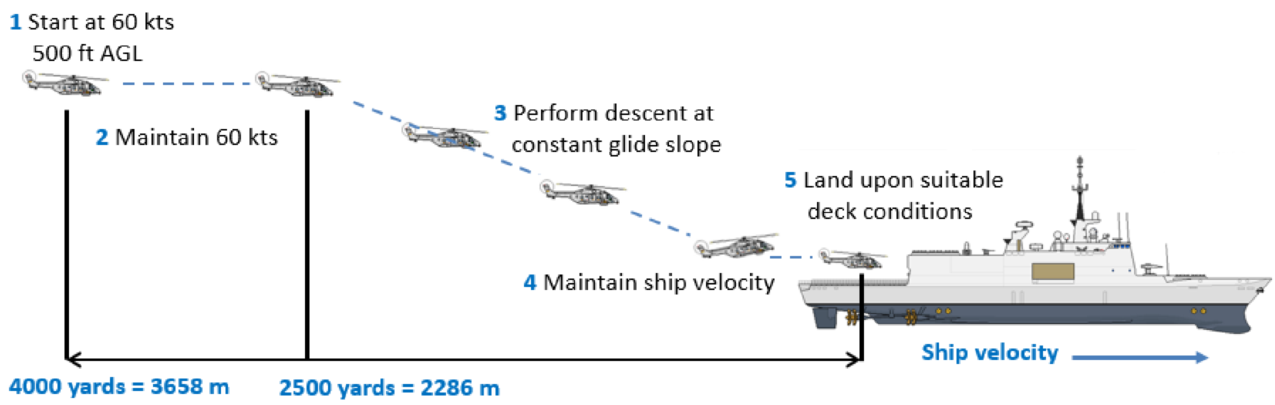

Figure 1 Deck landing Task - Straight In approach

2. SIMULATION ENVIRONMENT

This section provides a brief synthesis of the simulation environments used for the current study. All developments are performed on an "off-line systems development tool" that integrates all the components of the real-time ONERA simulator PycsHel which is a prototyping simulation bench dedicated to Vertical Take Off and Landing aircraft, located in Salon de Provence [6]. Additionally, evaluations are also performed at the Air Vehicle Simulator (AVES) located at DLR Braunschweig.

For the simulation set-up used at ONERA, the HOST code from Airbus Helicopters is used as the flight mechanic code in order to model an EC225 helicopter. Ship movements are generated using a model identified on the basis of experimental data on the deck movements of a Lafayette-class frigate. Additionally, the HOST code integrates a ship airwake model developed by ONERA in 1997 and based on wind tunnel measurement campaigns on a Lafayette frigate model. The frigate air-wake model and its implementation in the HOST code are detailed in [5].

The simulation set up at DLR involved AVES that represents DLR's research helicopter Active Control Technology/Flying Helicopter Simulator (ACT/FHS). The helicopter flight model is a nonlinear model based on DLR's research helicopter ACT/FHS and the in-house real-time nonlinear modeling program HeliWorX [22]. The helicopter model in HeliWorX also consists of an interface to simulate local aerodynamic effects by superimposing additional velocities from external wind fields like turbulent ship airwakes. For the ship model, a 6DOF hydrodynamic ship model was considered [23]. The ship dynamics was simulated using an in-house traffic server software VehicleControl.

3. TECHNICAL DEVELOPMENTS

For the proposed implementation, the complete approach and landing maneuver was divided into five different phases depicting five mission task elements. The considered scenario consists of a straight approach as depicted in Fig. 1. Prior to these five phases, and based on the knowledge of the ship positions, an automatic guidance towards the stabilized level flight at point 1 in Fig. 1 has been implemented. However, this automatic guidance scheme will not be detailed in the paper as the current study is dealing with "classical" flight guidance controller. Five different phases were defined as follows:

- Phase 1: Straight forward flight at constant velocity + constant altitude;
- Phase 2: Straight forward flight at constant velocity + descent at constant glide slope;
- Phase 3: Deceleration + descent;
- Phase 4: Straight forward flight at constant velocity + constant altitude;
- Phase 5: Hover over the deck + automatic landing.

In order to perform these different phases, a "Transition down" (TD) auto-pilot mode has been developed, enabling to switch between appropriate auto-pilot modes and instructions depending on the current phase along the entire maneuver. Depending on the maneuver phase, the auto-pilot mode engaged and their corresponding parameter targets are synthesised in Table 1.

A specific point above the deck has been defined. As illustrated in Fig. 2, this Deck Reference Point (DRP) is positioned at the deck center (landing grid), at a height corresponding to the Horizon Reference Bar (HRB) height.

The stabilised HRB is an illuminated bar remaining horizontal irrespective of the roll motion of the ship.

Table 1 Autopilot mode and targets depending on the maneuver phase

Phase	Auto-Pilot mode engaged	Auto-Pilot mode targets
1	IAS ALT HDG	60 kt 500 ft Ship heading + ship trajectory alignment (through roll)
2	IAS GS HDG	60 kt -3° Ship heading + ship trajectory alignment (through roll)
3	IAS GS HDG	20 kt Glide slope based on point above deck Ship heading + ship trajectory alignment (through roll)
4	IAS ALT HDG	Ship speed (10 kt) Height of the HRB (9.8 m) Ship heading + ship trajectory alignment (through roll)
5	HOVER Automatic Ship-Deck Landing mode (ASDL mode)	dx and dy Ship speed

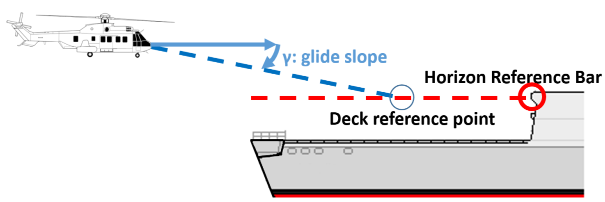

Figure 2 Deck Reference Point definition

This provides the pilot with a "True Horizon" reference whilst those lights fitted to the ship superstructure continue to show the ships actual angle of roll. In addition, the pilots also take into consideration the distance between the helicopter and the DRP (DIST) along with the distance deviations depicted as dx on the longitudinal axis, and dy on the lateral axis as illustrated in Fig. 3.

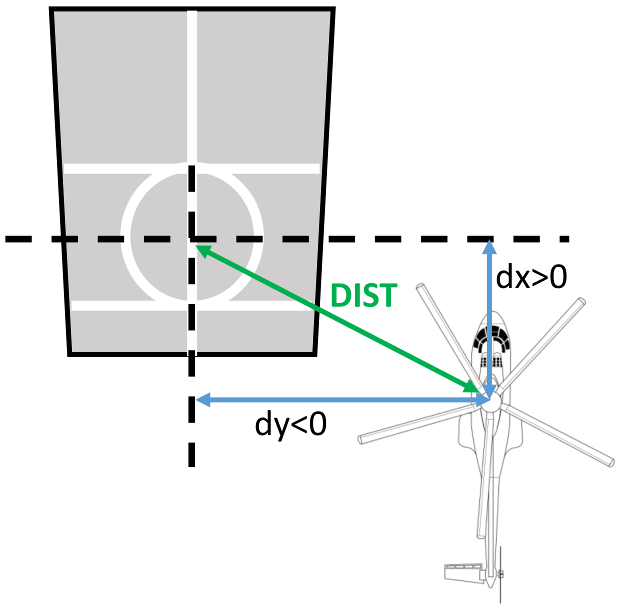

Figure 3 Helicopter positioning

3.1. Description of the modes

As mentioned before, the approach towards the ship is performed by using classical auto-pilot modes such as Indicated Air Speed mode (IAS), Altitude hold mode (ALT), Glide Slope hold mode (GS) and HeadinG hold mode (HDG).

These modes are automatically engaged by an upper mode called Transition Down mode (TD) following a logic that will be presented hereafter. These modes were previously developed at ONERA in the framework of an European project [6] and tuned for a tilt-rotor application. Within this study, no major modifications were needed, except the gains tuning to control an EC225 helicopter. Nevertheless, an

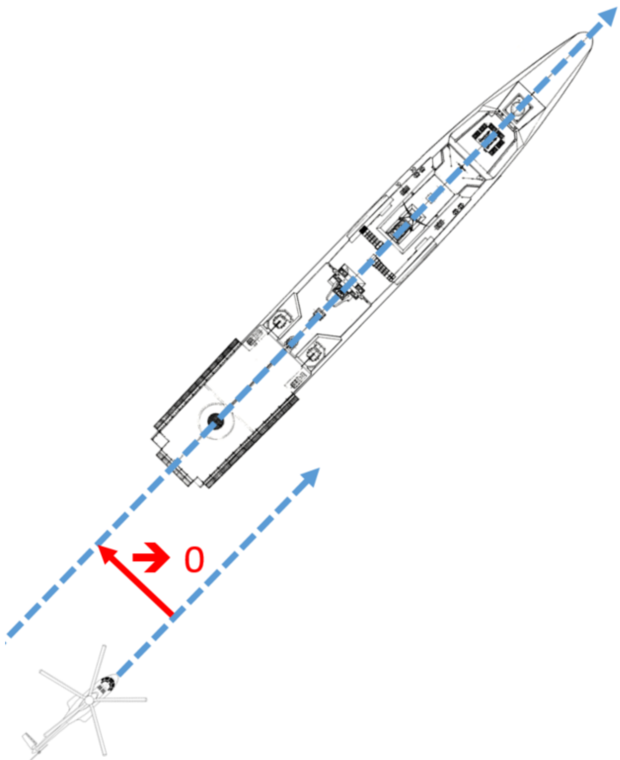

Figure 4 Helicopter alignment with ship's track

adaptation of the HDG mode was required, in order to align the helicopter with the ship track. Thus, the heading target is based on ship's track, while helicopter roll attitudes are adjusted to align the helicopter trajectory with the ship ones as depicted in Fig. 4.

3.1.1. TD mode and phase estimator logics

As mentioned before, the entire maneuver is split into five phases, corresponding to the engagement and disengagement of the auto-pilot modes and based on the distance between helicopter and DRP (illustrated in Fig. 2), called DIST, helicopter height and ground speed (GRS), longitudinal acceleration, dx and dy (defined previously):

- Phase 1: DIST >2442.7 m
- Phase 2: DIST <2442.7 m and HC height > 200 ft
- Phase 3: HC height < 200 ft and GRS > 22 kt and DIST < 90 m
- Phase 4: HC height < 40 ft and GRS < 22 kt and DIST < 46 m
- Phase 5: GRS=Ship speed (10 kt) and longitudinal acceleration < 0.1 m/s^2 and dx < 5 m and dy < 5m

3.1.2. HOVER mode

The proposed hover autopilot mode is based on a feedforward control strategy that integrates different options and features. For longitudinal and lateral axis, this mode integrates the two control modes namely, Velocity Hold and Position Hold (VH and PH). The detailed implementation of these modes can be found in [19], however their engagement was not automatically performed by the system. But as described before, it can also be automatically engaged by the TD mode.

The VH mode was designed to maintain the current helicopter speed at the moment the mode is engaged or the ship speed, considering that a data link between helicopter and ship is available. For the current study, VH relative to ship speed was used. Depending on the sea state, sway, surge and heave motions can lead to light helicopter speed variations and thus, attitude variations while the controller tries to precisely follow the ship speed variation. All speeds are considered in ground reference. Based on the difference between current helicopter speed and the targeted ship speed, pitch and roll angle targets are generated and an Attitude Hold controller (ATT) is used to follow these targets.

In addition to VH mode, a PH controller mode first places the helicopter at the DRP and then holds this position above the deck. This predefined position could be discussed and may be different when considering a manned or an unmanned machine. Indeed, a pilot would certainly perform the hover behind the ship in order to avoid the turbulent air wake generated by the ship structures and hangar. In this study, as considering an automatic management of the hover, it was always performed above the deck, in order to demonstrate the ability of the controller to counteract the turbulent airflow and maintain a relatively precise position.

PH mode is based on the distance deviations noted dx on longitudinal, and dy on lateral as previously shown in Fig. 3. Figure 5 details the logic of the Position Hold controller on longitudinal axis which is largely based on the VH mode. Hence, if the longitudinal distance deviation value is higher than 0.5 m (dx), a variation of 0.3 kt of the speed is performed by the VH mode in order to get closer to the reference position. Once dx value is lower than 0.5 m, VH controller maintains the ship speed.

For the HOVER mode, a PID contributes to the longitudinal cyclic controls as long as dx value is lower than 0.5 m. When dx is higher than 0.5 m, only a PD controller is applied. The same logic is applied for lateral repositioning. The only difference between longitudinal and lateral controllers being the speed

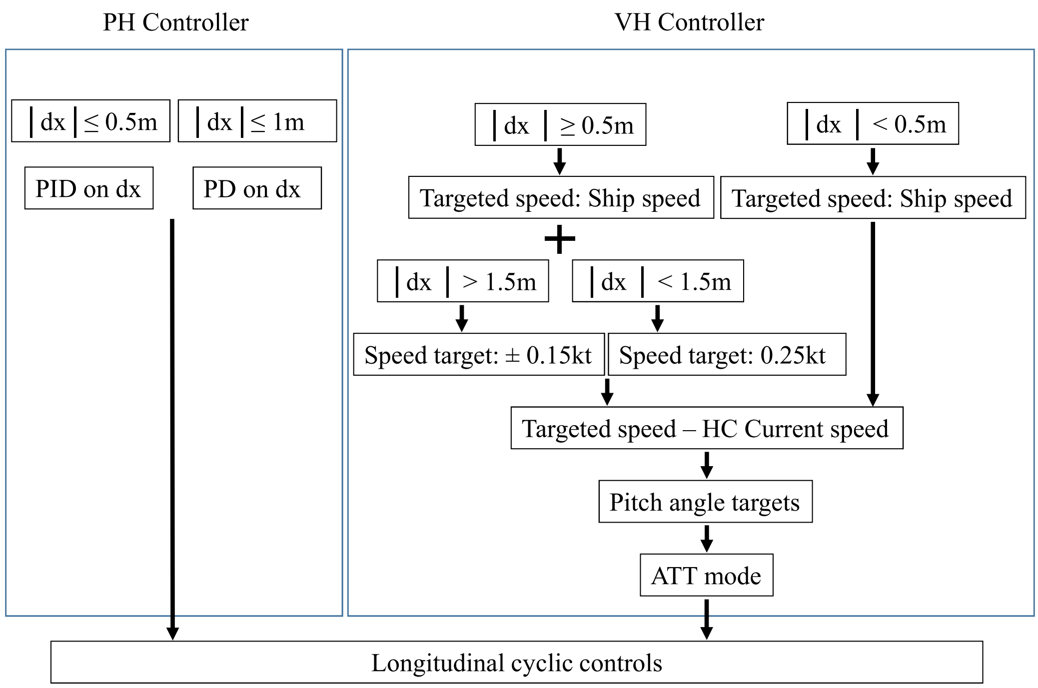

Figure 5 Position Hold controller logics on longitudinal axis

target taken into account by the VH controller when dy is higher than 1.5 m. Thus on longitudinal, it is set to 0.15 kt (as shown in the Fig. 5), while it is set to 0.25 kt on the lateral. The yaw axis is based on a feedforward control strategy to follow ship heading variations.

Through the collective, the HOVER mode follows the Horizontal Reference Bar, leading to continuously follow ship deck heave motions. The heave controller is largely based on ALT, altitude mode where altitude target is the HRB height.

As discussed in [24], the deck height can vary greatly depending on the sea state. As these variations in deck height can dangerously reduce the separation distance, the development of a deck avoidance function was initiated in order to avoid any unexpected impact between the helicopter and the deck. Nevertheless, feedback from a navy pilot indicated that as following the HRB height when performing the hover phase, the need of such a function was questionable.

It should be noted that engine and torque limitations are not introduced in the current controller design. However, these parameters are extremely important in such maneuvers, when continuously following the HRB height, or/and when performing the hover in tail wind conditions.

3.1.3. Automatic Ship-Deck Landing mode

Preliminary developments have also been performed to design an automatic ship-deck landing mode (ASDL), the goal is to automatically determine the time to initiate the final landing phase, and to perform the maneuver. For that, ship-deck heave motion estimation is performed, based on the ship motions on the vertical axis. It should be noted that it has been assumed that the data link is able to perfectly transfer all required ship parameters but delays, lacks or data alteration could be taken into account and analysed in the future.

The ASDL mode considers the maximum ship deck height reached previously and computes the maximum deck height period (called T), the final landing sequence is then launched in order to touch the deck when it reaches its maximum height as shown in Fig. 6.

The height of the deck is thus supposed to be precisely known by the system. Based on the deck height variations, the maximum height of the deck is

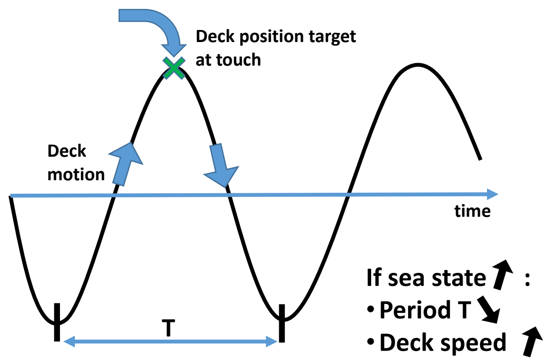

Figure 6 Deck position targeted at touchdown

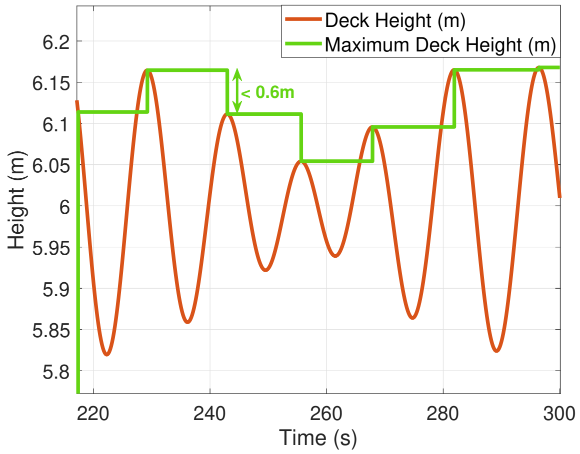

Figure 7 Deck height storage at each period

stored at each period as shown in Fig. 7. In addition, the period (T) of deck height variation is calculated (see Fig. 8).

A simple logic is then applied to determine the time at which the landing phase has to start. It is presented in the Fig. 9, the goal is to initiate the landing when the deck motions are getting lower.

This means when the difference in deck height between two periods is less than a given threshold (0.6 m), when the difference in deck height period between two periods is less than a certain threshold (set to 0.6 s), and when the helicopter is close to the landing grid (dx and dy less than 0.5 m). The time at which these four conditions are reached is added to the deck height period. A decision time constant, set to 4.75 s up to now, is then subtracted, finally giving the time at which the landing phase will be performed.

These threshold values could be re-evaluated for high sea states or, instead of being predetermined, could be evaluated in real-time depending on the current ship motions. The landing is then realised by

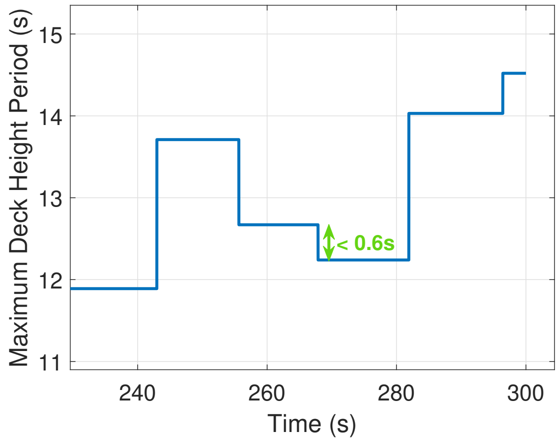

Figure 8 Deck height storage at each period

a decrease of the collective, while longitudinal and lateral cyclic controls continue to follow the landing grid position.

4. RESULTS AND DISCUSSIONS

4.1. Evaluation of the controller

The controller developments have been performed on an "off-line systems development tool" integrating all the components of the real-time ONERA simulator PycsHel. The evaluations of the system performances and different options developed were performed through off-line simulations and are discussed hereafter.

The considered scenario consisted of a Frigate model that follows a North route (0°) at a constant speed of 10 kt during the simulations. Nevertheless, this speed slightly varies depending on the sea state considered in the simulations. As proceeding to straight in approaches, the wind was aligned with the ship (azimuth 0°) with a magnitude of 10 kt.

4.1.1. Approach to the ship

Initially, the entire approach described in Fig. 1 was evaluated. Figure 10 represents the entire approach, starting at a distance of 2534 m from the DRP, with 10 kt of wind from North (Ship route). The yellow curve represents the TD upper mode phases all along the maneuver, switching from 1 at the very beginning to 5 at the end, corresponding to the hover phase.

In order to test the lateral repositioning during first phases, the helicopter was placed at 5 m on the right of the ship's track (see blue curve in Fig. 10).

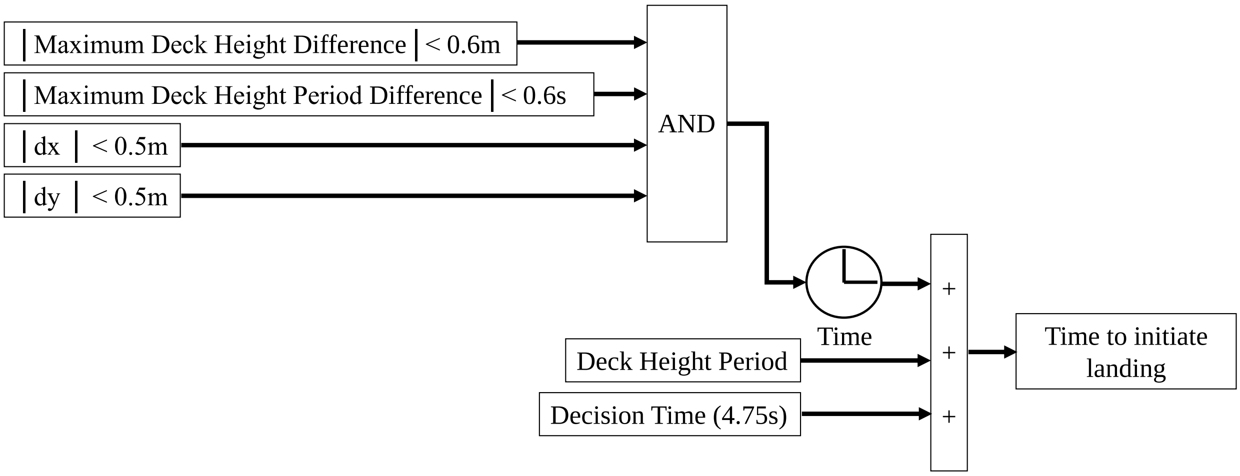

Figure 9 Logic to determine the time of landing phase initiation

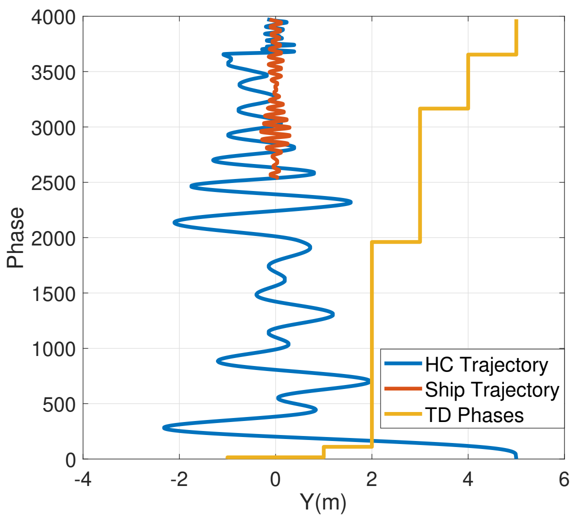

Figure 10 Helicopter trajectory during approach and landing phases

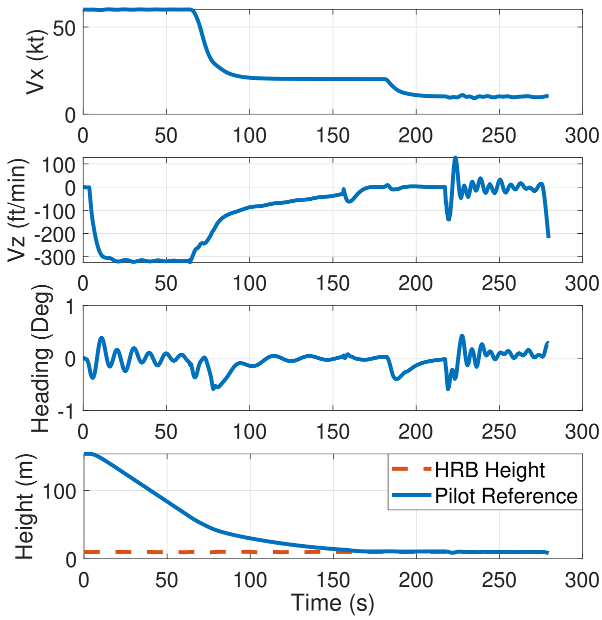

Figure 11 Helicopter parameters during the approach and landing phases

During the approach, the lateral deviation is always lower than 2 m, while it can be seen that there is an increase of the lateral motions in phase 3 during which the forward speed is reduced and the vertical speed adapted to capture the glide towards the DRP. In Fig. 11, the helicopter flight parameters are shown. Until phase 5, which initiates at 217 s, the forward ground speed Vx is well maintained to match the targets. Some transients can be observed on the vertical speed Vz, when transitioning from phase 2 to 3, and especially from phase 4 to 5. Nevertheless, these transients are very limited in time and have minor impact on helicopter height. It can be observed that the heading is very well kept during the whole maneuver, with maximum deviations of 0.5°. The precision on the yaw axis could be certainly relaxed during the approach.

The vertical path (height) corresponds to the targeted glide slope followed by the controller. The heights of different points are illustrated in Fig. 12. The altitude variations of these points during the hover phase up to the deck landing are shown in Fig. 13. It can be observed at around 217 s, the HOVER mode is automatically engaged. Then the pilot reference height is adapted to follow the Horizon Reference Bar height all along the maneuver. At 275.4 s, the automatic landing is initiated (green square), deck is touched at 279.5 s.

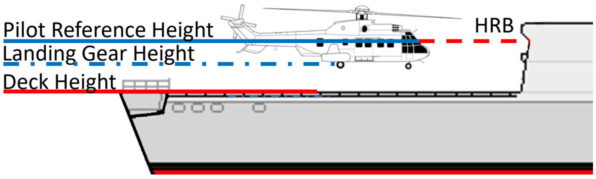

Figure 12 Heights during HOVER mode

4.1.2. HOVER mode performance

In order to estimate the performance of the HOVER controller, 10 simulations were performed in a scenario consisting of a sea state 4, ship speed of 10 kt and a wind of 10 kt considered from North. As shown on Fig. 14, the HOVER mode being not always engaged at the same distance from the ship, we analysed the performance of the controller once the helicopter is above the landing grid (red line) up to the deck touchdown (end of the plot). An analysis of the distances dx, dy during the hover phase, the distances at deck touchdown as well as the relative velocities in longitudinal and lateral at deck touchdown is presented in the following Table 2 and Table 3.

It can be seen that the average precision lateral positioning is better when compared to the longitudinal axis. The average distances from the landing grid during a hover phase are 0.368 m in longitudinal, and 0.02 m in lateral. The maximum dx distance observed being 1.12 m and for dy, 0.496 m.

At deck touchdown, the average precision in both lateral and longitudinal are almost identical. The average distances from the landing grid at touchdown are 0.174 m in longitudinal, and 0.198 m in lateral. The maximum distances observed being 0.63 m for dx, and 0.42 m for dy. Regarding the relative velocities, it is mandatory to have no horizontal relative speed with the deck (to avoid tire damages or skid sliding). While not null, these velocities are very limited, with an average of 0.316 kt and -0.06 kt respectively on longitudinal and lateral axis. The maximum relative velocity on longitudinal axis is 0.58 kt, -1.11 kt on lateral.

In Table 4, the roll and pitch attitude difference between ship and helicopter at touchdown are presented. In roll axis, the difference is very limited, but this is mainly due to very limited roll angle variations of the ship as well as of the helicopter. The pitch angle differences are mostly due to the helicopter pitch attitude at touchdown. The main differences can be seen on the heading, with a maximum deviation observed of 10.27°. If the constraints could be relaxed on the heading capture during the approach, a specific tuning of the gains to follow ship deck heading in hover would be certainly required.

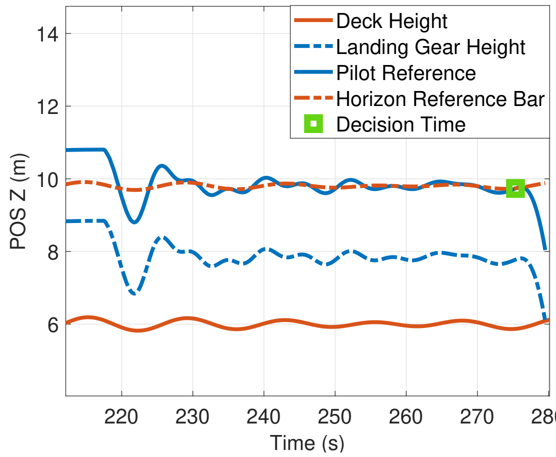

Figure 13 Heights during HOVER mode

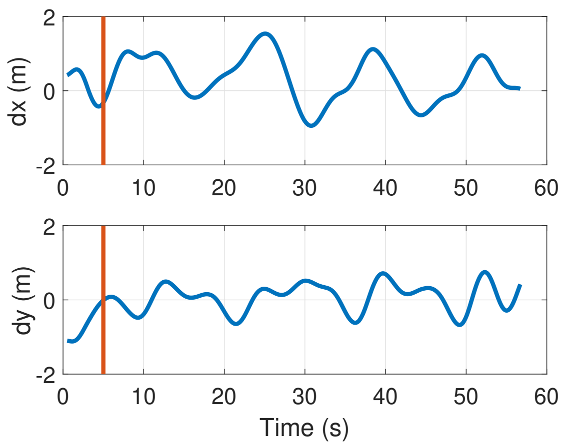

Figure 14 Distance between helicopter and landing grid during hover phase

4.2. Pilot Feedback and comments on the design of the maneuver

4.2.1. Pilot Evaluation

The proposed landing maneuver was also tested with two helicopter test pilots in the AVES located at DLR Braunschweig. Both the pilots are experienced with scientific flight testing for research and with subjective pilot rating methods. Both of them are qualified as experimental test pilots. Unfortunately, they do not have much experience with helicopter ship deck operations but as they have been participating in various pilot studies in the simulator, their feedback is highly valued in the context of this study. Furthermore, automatic flight control modes can re-

Table 2 Performances during hover phase

Trial Number	Mean dx (m)	Max dx (m)	Mean dy (m)	Max dy (m)
1	0.33	1.53	0.07	0.74
2	0.4	1.28	0.0009	0.61
3	0.41	1.02	-0.02	0.56
4	0.29	0.56	0.01	0.37
5	0.45	1.04	0.02	0.57
6	0.36	1.08	0.07	0.5
7	0.32	0.9	0.01	0.43
8	0.46	1.04	0.0009	0.36
9	0.19	1.77	0.04	0.45
10	0.47	0.99	0.0001	0.37
Average	0.368	1.12	0.02	0.496

Table 3 Performances at deck touchdown

Trial Number	dx (m)	Relative Long. Velocity (kt)	dy (m)	Relative Lat. Velocity (kt)
1	0.049	0.16	0.42	-1.11
2	0.33	0.48	0.17	0.15
3	0.28	0.19	0.06	0.09
4	0.07	0.13	0.15	-0.03
5	0.27	0.55	0.23	0.09
6	-0.25	0.56	0.24	0.11
7	0.35	0.06	0.06	-0.07
8	0.63	0.58	0.082	0.16
9	-0.36	-0.08	0.36	-0.03
10	0.38	0.53	0.21	0.04
Average	0.174	0.316	0.198	-0.06

Table 4 Relative Attitude at touchdown

Trial Number	Roll angle (deg)	Pitch angle (deg)	Heading (deg)
1	0.16	-1.26	-2.21
2	-0.1	-0.29	-10.27
3	0.05	-2.46	-5.76
4	0.16	-2.15	-6.78
5	0.3	-2.93	-5.9
6	-0.39	-3.24	-5.85
7	0.06	-1.72	-6.1
8	0.46	-1.99	-3.68
9	-0.2	-2.34	-7.67
10	0.25	-2.62	-5.82
Average	0.075	-2.1	-6

duce the pilot workload significantly, therefore pilot feedback is highly valuable to test the improvements in safety and efficiency of the control modes.

However, the current study aimed to only thoroughly assess the proposed five phases of the whole automatic approach and landing maneuver to evaluate its effectiveness in simulating a realistic operational scenario. To achieve this objective, pilots were asked a set of questionnaires. The pilots performed simulations of the whole maneuver in the Air Vehicle Simulator and contributed their perspectives about the credibility of the maneuver in a realistic maritime scenario. As the number of pilots is limited, the main aim of the evaluation was to assess the maneuver qualitatively.

Even though the outcome of the study is not a direct comparison of the efficiency of the automatic controller over the pilot flown automatic and augmented modes, it gives an indication of improvement and variation in the task performance for such a mission. The feedback from the pilots during the design phase of the complete maneuver after performing the simulations in AVES based on the set of questionnaires asked is summarised below:

1. Choice of speed on Hover mode engagement (Velocity Hold option):
   Both the pilots preferred the ship speed instead of current helicopter speed to be matched during activation of Hover mode. The pilots commented that be it an automatic maneuver or a piloted, it is easier because one does not have to estimate the ship speed.

2. Precise velocity following versus corrections made at regular intervals:
   Pilot 1 commented it might be more useful to have the corrections made when the gap between ship and helicopter parameters is small in order to avoid high frequency response from the helicopter. However, Pilot 2 also preferred to have a possibility to switch the automatic and piloted modes by pressing a button in case the helicopter gives high frequency response in order to take authority to manage the task.

3. Are the continuous (light) attitude variations caused by the controller trying to follow the ship speed acceptable?
   Both the pilots mentioned that it is acceptable and normal that the helicopter would have some motion and small attitude and speed changes. If these variations are within the desired limits, then they are acceptable.

4. Relative position of the helicopter to the ship at AP engagement versus pre-defined position on (above) the deck:
   Both the pilots preferred the ship deck position to be the most suitable.

5. Are the continuous (light) attitude variations caused by the controller trying to follow the ship position acceptable?
   One of the pilots mentioned that it depends on how big the distance variations are. So if the distance variations are small (in desired and adequate limits), then the attitude variations will be small and that is acceptable. However, if the variation is big e.g. 50 m, that would cause big attitude variations, in such a case we need to find a trade off having an exact position or fewer attitude variations.

6. Viewpoint about Automatic Mode engagement:
   Pilot 1 mentioned that the pilot must have the control to engage the mode. Additionally, for a Position Hold mode, it should not engage if you are too far away from the position. However, Pilot 2 specified that an automatic engagement is also good. Although if the maneuver is too rapid then manual mode is preferable. The combination of both could be useful as well, so in general automatic but the pilot should be able to overwrite it.

7. Suggestions for additional parameters in the logic to initiate the landing maneuver:
   Pilot 1 suggested that it could be useful to use roll angles if the helicopter is too close to the center line. Pilot 1 also indicated it might be also useful to consider other angular variations as well. According to Pilot 2, the wind direction could also play a role. Additionally, ship motion could vary based on the wind and would not be an ideal condition to land. Therefore, it could be useful to incorporate wind conditions including wind speed and direction.

As the purpose of the pilot evaluation was to assess the suitability of maneuver for such a mission, not much stress was laid on the controller choice and performance within the scope of this study. Even though the pilots performed the maneuver using three different augmented modes, only one example using TRC combined with ship relative Position Hold is demonstrated in the current study as the focus remains the automatic ship deck landing controller. Fig. 15 shows the forward velocity during the final phase of the approach and descend followed by 30 s hover over the ship deck using TRC combined with PH. No deck landing was performed specifically in this case.

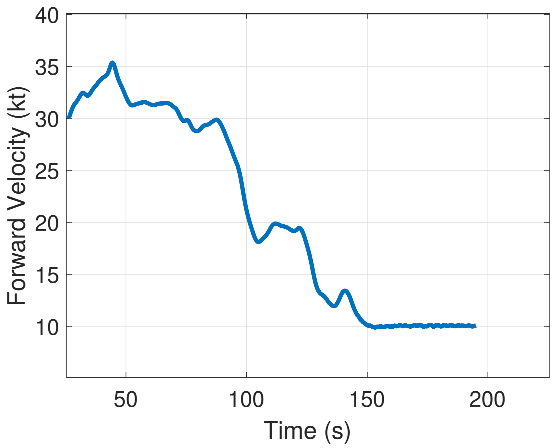

Figure 15 Forward velocity of the helicopter during approach, descend and hover

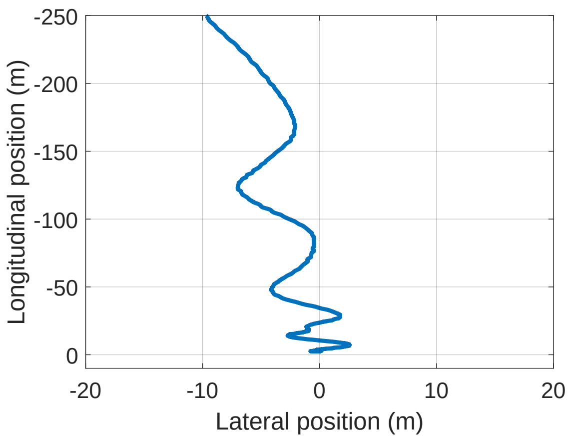

Figure 16 Helicopter position relative to deck center during the approach, descend and hover

Fig. 16 illustrates the helicopter position relative to deck center during the approach, descend and hover over deck. The position and velocity both are in desired or adequate limits. However, pilots still have to do effort to perform the approach manually. Even though the hover was performed completely hands-off and autonomously, the pilots commented it was not easy to find a suitable position to start the hover. This indicates how useful it can be to perform the complete maneuver automatically in order to improve the overall safety for the pilots for such an operation.

4.2.2. Pilot Feedback for further improvements

DGA-EV (French Flight Test Center) organised an exchange with a navy pilot to have a feedback on the effectiveness of the whole scenario as well as the automatic ship deck landing controller. Please note no evaluations were performed in the simulator but a general description of the implemented phases of the maneuver and the controller demonstration was provided. While the general technical approach was validated, a number of points requiring particular attention were outlined:

- For instance, it was outlined that ship stabilisation should be taken into account, and more particularly the roll stabilisation. It should be noted that while stabilising the roll motion of the ship induces larger ship heading variations than usually considered and as these yaw motions are complex to follow (by the pilot and thus probably by an automatic system), this should be integrated in ship motion models.
- Considering a straight-in approach with headwind is a start, but other operational cases should be considered to better evaluate the system robustness. In particular, test cases involving tail wind / three-quarter tailwind, which are often realised in operation. In these conditions, turbulence due to the proximity of the hangar are lowered, but ship motions are completely different as the waves are impacting the ship from behind. From the helicopter performances perspective, this requires more power with smaller power/torque margins as the airspeed is reduced.
- As previously indicated, engine and torque limitations were not introduced yet in the controller, however these parameters are extremely important in such maneuvers. Pilot laid emphasis on also considering One Engine Inoperative case when decelerating close to the ship (Phases 3-4). The automatic controller should integrate the possibility to perform a go-around or to perform the landing depending on the position of the helicopter at the occurrence of the loss of one engine.
- The pilot indicated that the landing phase is not always performed vertically. Thus, pilots prefer performing a deck landing with a low longitudinal speed on some helicopter types, such as the "Panther" (Military Dauphin) for example.

It was also indicated that during the final landing phase, pilots try to hold constant helicopter attitudes. Some simulations were done where cyclic controls were managed to maintain the current helicopter attitudes (through an ATT mode) instead of following the landing grid position (HOVER mode). But this contributed to degrade the performances at deck touch (final position with respect to the landing grid). A trade-off between attitude variations and position hold should be further investigated if this is really essential for pilots.

5. POTENTIAL FUTURE DEVELOPMENTS

While the overall performances of this automatic controller are promising, the HOVER mode performances are degraded at higher sea states due to much larger ship motions. As one might expect, increasing the wind magnitude and the level of turbulence also decrease performances. As outlined previously, the different threshold values used in the controller should be adapted (ideally evaluated in real-time) for high sea states, for larger ship deck height and attitude variations.

Therefore, based on pilot feedback described in the previous section and considering the current results and limitations, following developments could be considered to improve the implemented automatic flight control modes in future research:

- Further optimisation will be done on the automatic ship-deck landing controller that also integrates a deck motion estimator.
- Piloted simulations will be performed to assess the benefits of the automatic modes and handling qualities ratings.
- Further optimisation of the automatic control modes involving improved disturbance rejection properties.

The initial objective of the collaboration project was that DLR will concentrate on evaluating and investigating these implemented control laws. However, an exchange mobility having a duration of six months has been organised, where the DLR representative is working at ONERA. Thus, investigations will be performed to adapt the ONERA controller, to improve the disturbance rejection properties and find the trade off between disturbance rejection performance and stability margins. It is also expected to perform evaluations in the ONERA simulation environment with a DGA-EV pilots. In this way, a clear comparison can be performed for two different helicopter types and two different simulator environments.

6. CONCLUSIONS

In the framework of the cooperation between DLR and ONERA, an Automatic Ship-Deck Landing controller consisting of an automatic transition down upper mode has been developed and tested for different phases of the approach and landing through off-line simulations integrating a complete maritime simulation environment. The simulation results demonstrate the following key points:

- The implemented Transition Down upper mode enables the realization of the entire maneuver, from the stabilised level flight to the over the deck hover and final landing phase automatically managed.
- In the considered scenario (wind magnitude= 10 kt, sea states <= 4), the overall performances are very good during all phases of the maneuver. The preliminary developments of the automatic landing, integrating a deck motion estimator, also show very promising results.
- The pilot evaluations of the maneuver indicate the suitability of the maneuver for a realistic ship deck landing mission.

Nevertheless, some additional modifications have to be realised to improve the performances of this upper mode for higher sea states and wind conditions. In addition, only a very limited number of test conditions were studied up to now, and more complex test cases would have to be investigated to cope with more realistic operational situations.

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