INVESTIGATION ON THE SIMULATION OF HELICOPTER/SHIP OPERATIONS

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Key words: Dynamic inflow, Ground effect, Helicopter/ship operations, PID controller

Abstract: The goal of the present paper is to describe the ongoing effort at Delft University of Technology to develop a modeling and simulation tool capable of reproducing helicopter flight operations near ships. The paper will concentrate mainly on pilot modeling issues showing how the pilot controls are affected by the fidelity used in modeling the rotor dynamic inflow in-ground-effect. The main rotor inflow is modeled with a three and six state Peters-He finite-state model, modified to take into account sideward flight. To account for the effect of ground proximity on the rotor inflow a ground model is included and adapted to represent a finite-width ship deck. The ship motion is modeled by using the US Navy "Ship Motion Program." The paper simulates the fore/aft landing procedure of the IAR 330 Puma SOCAT helicopter of the Romanian Navy to the deck of a Type 22 frigate. The pilot is modeled by a classical PID controller, using gain scheduling for the different phases of the maneuver. The paper demonstrates that the main contribution to the increase in pilot workload during ship approach lies in the ship's dynamic heaving motion, this influence being reflected in the form of constant adjustments to the collective control angle.

INTRODUCTION

The behavior of large helicopters operating in a maritime environment is different from helicopters performing land-based operations because of the interaction with the moving landing platform. The presence of wind, turbulence and low visibility can result in a high workload for the pilot. In addition, helicopters are notorious for strongly coupled off-axis response during maneuvering flight [1]. It is therefore that high-fidelity flight simulation models are needed to support helicopter ship-based flight testing, pilot training, and operational analysis.

While hovering at close proximity to an inclined ground plane, partially above the edge of a rolling, pitching and heaving deck, not only the magnitude of the rotor inflow, but also the distribution of inflow over the rotor disk affected, influencing the helicopter dynamics. The work by Xin et al. [2-6] has enabled the modeling of in-ground-effect rotor inflow for this type of conditions, encountered during helicopter/ship operations. Based on the finite-state model, it can be implemented relatively straightforward in simulation models using a finite-state representation of the main rotor inflow. For example, Basset et al. [7] have extended their flight simulation model with this ground effect model, noting however that "in forward flight, when using more combinations to describe the rotor and ground distributions, the model may appear time consuming and some problems of convergence may occur during the trim process."

Related to this notion, Prasad et al. [8] have investigated the use of an off-line trained neural network for the required calculations, showing that a neural net could be used for the application of the model in real-time simulations.

Later research by Xin et al. has focussed on using three-dimensional panel methods to model the coupled helicopter/ship interference [9, 10]. He et al. [11] have extended this work is including the effect of the ship's airwake and turbulence.

The effect of ship motion on pilot control has been investigated by Colwell [12]. Focusing on hovering above a deck, he concluded from test data that collective control is tightly correlated to the ship's vertical motion, but not with the pitch, roll or lateral motion.

Recently, a nonlinear helicopter model for piloted simulations has been developed at the Faculty of Aerospace Engineering [13]. This so-called *Helix* consists of a generic mathematical model written in Fortran 90/95, a set of trim and linearization routines, and a link to Matlab/Simulink to run the simulations. By running the simulations in Simulink one can take advantage of Simulink's set of control design tools and solvers. Due to the modular build-up, the program can easily be extended with new routines to increase the fidelity of the mathematical model.

This paper describes the ongoing effort to further develop this simulation tool and make it capable of reproducing helicopter flight operations near ships. To increase the fidelity of *Helix* in simulating these type of operations, the effect of ground proximity on the main rotor inflow is included in the mathematical model, adapting the model of Xin [2] to represent a finite-width ship deck. *Helix* is then used to investigate the effect of the ground effect model fidelity on pilot control, by simulating a standard fore/aft approach. For this, the application of the Romanian IAR-330 Puma SOCAT for naval use on Type 22 frigates, part of a project within the Centre of Knowledge Romania-The Netherlands [14], is considered.

This paper is structured as follows: section 1 discusses the rotor inflow in-ground-effect model incorporated in Helix, as well as the ship motion model used during the simulations. Section 2 presents the pilot model used to fly the standard fore/aft approach, while the results of the simulations are treated in section 3. Finally, in section 4 the conclusions from the present paper are drawn.

1. MODELING ROTOR INFLOW IN GROUND EFFECT

In this section the modeling of the main rotor inflow and effect of ground proximity on this inflow will be discussed.

1.1 Main rotor inflow

The mathematical model of *Helix* uses the well known Pitt-Peters finite-state model [15, 16] to represent the dynamic behavior of the main rotor inflow. To be able to incorporate the proposed ground effect model, the mathematical model has been extended with the more general Peters-He inflow model [17, 18]. In this model, the induced inflow λ_i is represented by a summation over the dimensionless radius $\bar{r}$ and the azimuth angle ψ [17]:

$$\lambda_i(\bar{r},\psi)=\sum_{r=0}^{\infty}\sum_{j=r+1,r+3,...}^{\infty}\phi(\bar{r})[\alpha_j^r\cos r\psi+\beta_j^r\sin r\psi] \tag{1}$$

In here, α_j^r and β_j^r are the inflow coefficients, and ϕ is a radial function. The inflow coefficients vary in time via:

$$[M]\begin{Bmatrix}\dot{\alpha}_j^r\\ \dot{\beta}_j^r\end{Bmatrix}+[V][L]^{-1}\begin{Bmatrix}\alpha_j^r\\ \beta_j^r\end{Bmatrix}=\frac{1}{2}\begin{Bmatrix}\tau_n^{mc}\\ \tau_n^{ms}\end{Bmatrix} \tag{2}$$

where M is the apparent mass matrix, V the velocity matrix and L is the gain matrix. The pressure coefficients on the right hand side depend on the loading at the rotor disk.

At the moment, only a three and a six state model is implemented in *Helix*. This restriction on the number of states is based on previous research showing that five states are required to match results obtained with CFD analysis [19]. Initially, up to 15 states were implemented, but the extra states had no influence on trim and simulation results, whereas the increase in states had a negative impact on the temporal performance.

A shortcoming of the Peters-He models is that it treats the rotor wake as quasi-steady, assuming that wake bending due to rotor pitch and/or roll takes place instantaneously, while in reality, it does take some finite time to develop the wake curvature. Due to the gyroscopic behavior of the rotor, this discrepancy results in an incorrect off-axis response to cyclic inputs [20]. To overcome this problem, *Helix* was extended to include the wake distortion dynamics modeled, according to Zhao [21], as an extra set of states; lateral and longitudinal wake curvature, wake spacing and wake skew.

To be able to use the model in sideward flight, an extra transformation was added to the Peters-He model that takes into account a sideward speed component [22].

1.2 Ground effect modeling

In ground proximity, the rotor induced inflow is reduced due to a decrease in required thrust. Near a moving finite platform, not only the magnitude, but also the distribution of the inflow is affected, and a simple uniform reduction factor will not suffice. Instead, the platform can be modeled by a source-like distribution, causing an ‘upward’ inflow λ_G, or a reduction in induced inflow [2]:

$$\lambda_i^{IGE}=\lambda_i-\lambda_G \qquad \text{or} \qquad \begin{Bmatrix}\alpha_j^r\\ \beta_j^r\end{Bmatrix}^{IGE}=\begin{Bmatrix}\alpha_j^r\\ \beta_j^r\end{Bmatrix}-\begin{Bmatrix}\varepsilon_j^r\\ \zeta_j^r\end{Bmatrix} \tag{3}$$

where ε_j^r and ζ_j^r are the upward inflow coefficients. As developed by Xin [2], the pressure representing the ground plane can be written in the same form as the pressure at the rotor disk used in the Peters-He model. This results in a similar form for the upward inflow at the rotor disk. For the static case, this is:

$$\lambda_G(\bar{r},\psi)=\sum_{r=0}^{\infty}\sum_{j=r+1,r+3,...}^{\infty}\bar{P}_j^r(\bar{r})\left[\varepsilon_j^r\cos r\psi+\zeta_j^r\sin r\psi\right] \tag{4}$$

where $\bar{P}_j^r$ is the dimensionless associated Legendre function of the first kind. The upward inflow coefficients are related to the rotor pressure coefficients via the so-called ground influence matrix G:

$$\begin{Bmatrix}\varepsilon_j^r\\ \zeta_j^r\end{Bmatrix}^S = \frac{1}{2}[G]\begin{Bmatrix}\tau_n^{mc}\\ \tau_n^{ms}\end{Bmatrix} \tag{5}$$

The elements of this matrix depend on the position of the rotor hub with respect the deck's edge, the pitch and roll angle of the deck and the flight speed. Note that there is no dynamic component, as changes are assumed to be instantaneous. Whereas the original model of Xin only takes into account a single edge platform, the present paper has used a finite-width strip to represent the ship's landing platform. As will be discussed in Section 3.1, during the simulated approach the helicopter will perform a sidestep to get above the landing zone, and the effect of the rotor possibly extending at the stern will be smaller than the effects due to the crossing of the side of the ship.

The decrease in inflow caused by the platform dynamics are modeled by:

$$\begin{Bmatrix}\varepsilon_j^r\\ \zeta_j^r\end{Bmatrix}^D = \frac{1}{2}[C]\begin{Bmatrix}\gamma_i^{pc}\\ \gamma_i^{ps}\end{Bmatrix} \tag{6}$$

where ε_j^r and ζ_j^r are again the upward inflow coefficients and C is the ground velocity influence matrix. The velocity coefficients on the right hand side are directly related to the pitch, roll and heaving velocity, written as:

$$g = g_0 + g_c \cos r\psi + g_s \sin r\psi \tag{7}$$

where g_0 is the dimensionless heaving velocity and g_c and g_s are the dimensionless pitch and roll rate, respectively. The implementation of the model has been verified by using *Helix*' trim routine, comparing the results with "rules of thumb" on the effect of velocity and altitude. Above an hub altitude $z_h/R = 2$ and for a flight speed above $V = 2v_h$ the ground effect should be diminished, as confirmed in Figure 1. In this figure, the uniform inflow coefficient α^0_1 is plotted for increasing trimmed flight speed, at various altitudes measured in dimensionless rotor hub height. At $z_h/R = 2$, the effect of ground proximity is less than 3% compared to the out-of-ground-effect case, while above $V = 23$ *m/s* the effect has indeed vanished.

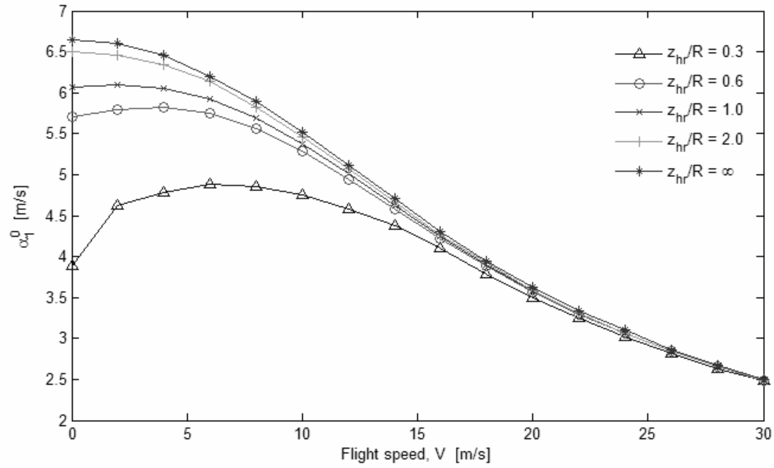

Figure 1: Trimmed uniform inflow component for increasing flight speed at various altitudes

Unfortunately, at this moment the simulation part of *Helix* is only able to cope with the ground effect model in hover, due to the amount of computational power required to calculate the elements of the ground influence matrix, as also noted by Basset et al. [7]. In forward flight the computation of a single matrix [*G*] takes in the order of seconds, whereas in hover this is 2 orders lower. However, at low speeds the decrease in ground effect effectivity is small, especially at the altitude where the simulation runs for this paper were performed. Downside of this approach is the loss in coupling effects occurring due to the backward sweep of the wake.

1.3. Ship motion

The ship motions used as input for the ground effect model are obtained from a Simulation Time History (STH) program, developed at the Carderock Division of Naval Warfare [23]. The 6 degree-of-freedom model is based on transfer functions from the Navy's Standard Motion Program (SMP) and provides the time histories for both the displacements and the rotations, i.e. surge, sway, heave, roll, pitch and yaw. Waves can either be unidirectional or spread over a -90°, 90° range with respect to the dominant direction. The main input parameters required to run the program are:

- Ship speed
- Wave height
- Wave direction with respect to ship's longitudinal axis
- Modal wave period

The wave height and modal wave period are related to the wind speed via the so-called sea states, as defined by the Pierson-Moskowitz scale [24]. Unfortunately, STH is only able to produce 20 seconds of time history, and the binary SMP input file could not be read using an adapted and recompiled version of STH. To overcome this problem, the obtained time histories are lengthened by using a sinusoidal filter, and are where necessary manually processed to remove discontinuities in the time derivates. One could question the validity of this overlapping method for higher sea states, where the wave period is more than 10 seconds and the random nature of the waves is lost. Figure 2 shows the processed output for a ship sailing at 5 *m/s* in a sea state 4. Table 1 presents the characteristics of the sea states used in the simulations.

Table 1: Sea state characteristics

Sea state	Wind speed [*kts*]	Wind force [*bft*]	Wave height [*ft*]	Wave period [*s*]
1	4-6	2	1	1.5
4	17-21	5	6	4.5
6	28-33	7	10	8.5
9	61-69	10	20	17.5

2. PILOT MODELING

Originally, *Helix* was equipped with an inverse simulation based SYCOS controller [25, 26] to model the pilot's behavior. The controller requires a predefined path as an input, and using a inverse linear model of the helicopter the control inputs are determined. However, the implemented pilot model uses the velocities along the path as a reference, instead of the relative position to the landing spot. As using positional references to fly near obstacles is more intuitive, and realistic, the SYCOS controller has been replaced with a classical PID controller.

2.1 Stabilizing control

To stabilize the helicopter throughout the whole maneuver, a proportional and differential gain matrix is used that couples 9 helicopter body states to the 4 control inputs. The 9 body states include the linear velocities *u, v, w*, rotation rates *p, q , r* and Euler angles φ, θ and ψ.

The entries of the gain matrix have been obtained from the linearized model using pole placements techniques. At a flight speed of 5 *m/s* (the velocity at the start of the approach) the Bode diagram of the linearized model shows an increase in control authority between 0.5 and 0.6 *Hz*, near one of the eigenfrequencies of the system. By using the linear model in a proportional feedback system the eigenvalues of the closed-loop system can be set in the optimum frequency range by using pole-placement techniques. For this, a standard damping of 0.7 is assumed.

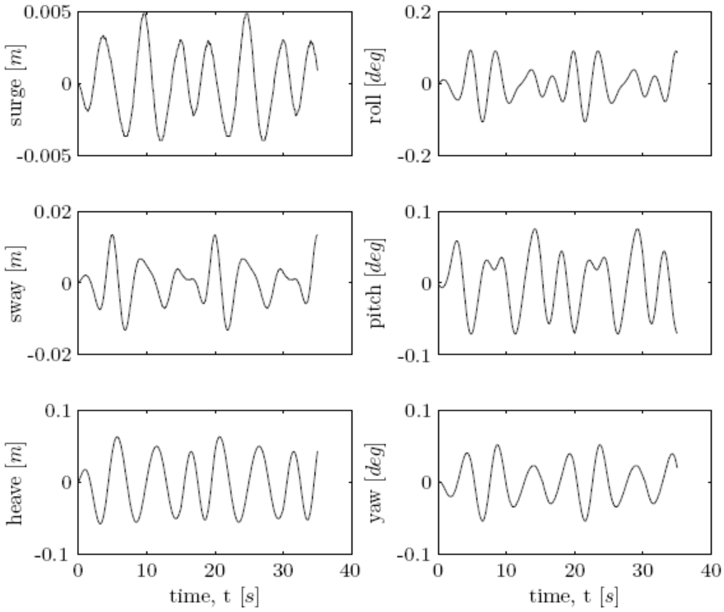

Figure 2: 35 second ship motion time history in sea state 4, sail speed 5 m/s

As expected, the correlations between lateral cyclic and roll rate and roll angle, and between longitudinal cyclic and pitch rate and pitch angle, are dominant. For a flight speed of 5 *m/s*, the velocity at the start of the approach, this gain matrix is:

$$K_P = \begin{array}{ccccccccc|c} u & v & w & p & q & r & \psi & \theta & \phi & \\ 0.0019 & -0.0002 & -0.0026 & -0.0013 & -0.0794 & 0.0015 & -0.0003 & -0.0218 & -0.0051 & \theta_0 \\ 0.0044 & 0.0000 & 0.0012 & -0.0003 & -0.4134 & 0.0000 & 0.0000 & -0.2790 & -0.0003 & \theta_{1s} \\ 0.0001 & -0.0006 & -0.0001 & 0.0640 & -0.0045 & 0.0139 & 0.0081 & -0.0023 & 0.0573 & \theta_{1c} \\ 0.0021 & -0.0017 & -0.0028 & -0.1870 & -0.0874 & 0.0358 & -0.0012 & -0.0252 & -0.1885 & \theta_{0t} \end{array} \qquad (8)$$

2.2 Maneuvering control

On top of the stabilizing PD controller, a set of PID controllers has been added to fly the approach, one for each control variable. By using a gain schedule, the different phases of the maneuver as presented in the next section each have a separate controller. To prevent the PD and PID controllers from counteracting each other, the related values are removed from the gain matrix when necessary. The values of the proportional, integrative and differentiating gains are manually fine-tuned, starting with the values proposed by Van Holten [27].

As a reference, the controller uses the three-dimensional position of the landing spot. However, to prevent it from tracking small, high frequency displacements, a low frequency pass filter is applied to the ship's x and y displacements, with a cut-off frequency of 10 *Hz*.

As an example, the combined, the implemented controller for the first part of the approach is depicted in Figure 3. In here, the triangle K_P represents the stabilizing PD controller, whereas on top of that two of the control inputs are governed by a PID controller.

3. SIMULATION

In this section the flight profile for simulated the fore/aft approach will be introduced, followed by a discussion on the simulated ship motion. Finally, the results of the simulation runs will be presented.

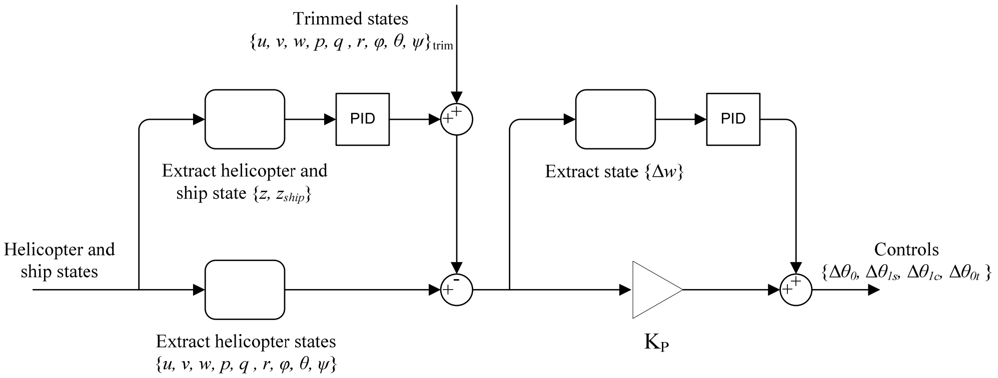

Figure 3: Combination of PD and PID controller for altitude control as implemented in Helix

3.1 Flight profile

The present paragraph will discuss the simulated approach of Romanian IAR- 330 Puma for naval use on a Type F-22 frigate. A common landing procedure is the fore/aft approach, as depicted in Figure 4. This maneuver can be split in several distinct phases:

- A decelerating approach from far behind the ship to positional hold at port side.
- Hover alongside the ship deck.
- Sideward step to station keeping.
- Station keeping above the landing spot.
- Descent onto the ship deck.

As the focus of this research is on the effect of the in-ground-effect rotor inflow on pilot controls, the simulated approach starts at the period of hover alongside the deck. The different phases of the approach are initiated on a fixed time, as shown in Figure 5. The initial flight speed is 5 *m/s*, the initial position of the helicopter's center of gravity 25.7 *m* above the flight deck and 30 *m* next to the landing spot, on port side. Figure 5 also shows the landing spot position in time, as tracked by the pilot model.

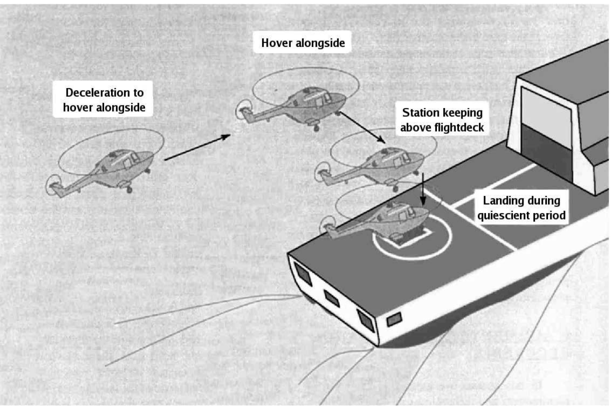

Figure 4: Fore/aft landing procedure

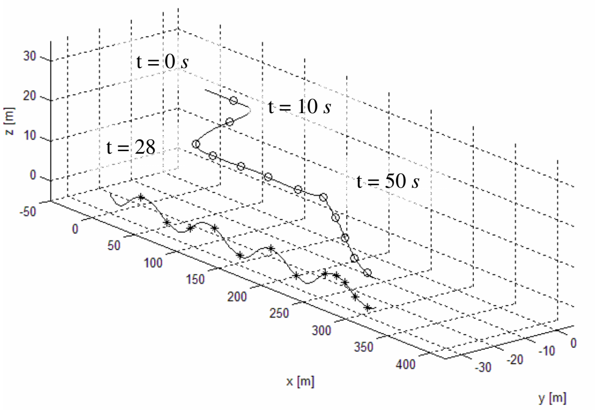

Figure 5: Timing during simulation of fore/aft approach, in sea state 9

3.3 Simulation cases

The approach has been simulated for different sea conditions, using different inflow models and ground effect models. In this way, the effect of increasing fidelity on pilot workload can be investigated. In short, the cases are:

- Uniform, Pitt-Peters, three and six state Peters-He inflow models
- Static and dynamic ground effect
- Sea states 1, 4, 6 and 9

Logically, the ground effect models are only used in combination with the Peters-He inflow model. In the next section, combinations of cases are used to illustrate the results.

3.4 Simulation results

First, the effect of the inflow model type and the number of inflow states on the pilot controls has been investigated. Figures 6 and 7 present the control inputs and main rotor inflow coefficients during the approach for the 4 different inflow models, and as expected the differences are negligible. The uniform inflow model shows more abrupt control changes, probably due to a lack of dynamic coupling.

To investigate the effect of an increasing ground effect model fidelity on simulated pilot controls, a comparison is made between a static and a dynamic ground effect model. The first includes a partial and rotated platform, the latter adds heaving and both pitch and roll velocity. Figures 8 and 9 show the effect of the two models on the control inputs and the uniform inflow component of the six state Peters-He model, respectively, for an approach in sea state 4 and 9. The dominance of the effect of platform dynamics over the effect of the platform static position is well visible. The effect of the heaving velocity on the uniform inflow is of a larger magnitude than the effect of the rotational velocities on the other inflow coefficients. The fluctuating inflow causes an increase in pilot workload, most prominent in the collective control. These observations are partly in line with the conclusions of Colwell [12], stating that collective control has a strong coupling with the ship's heaving motion. However, Colwell showed a tight correlation between collective and heaving acceleration, whereas the performed simulation shows a direct relation to the heaving velocity. This is probably due to the fact that the input for both the pilot and rotor inflow model is restricted to the position and the velocity of the ground plane.

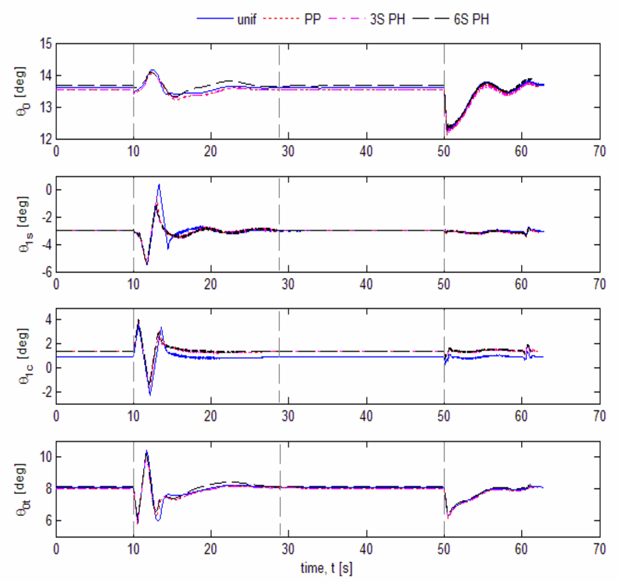

Figure 6: Control inputs during approach to a ship deck in sea state 6 using different inflow models

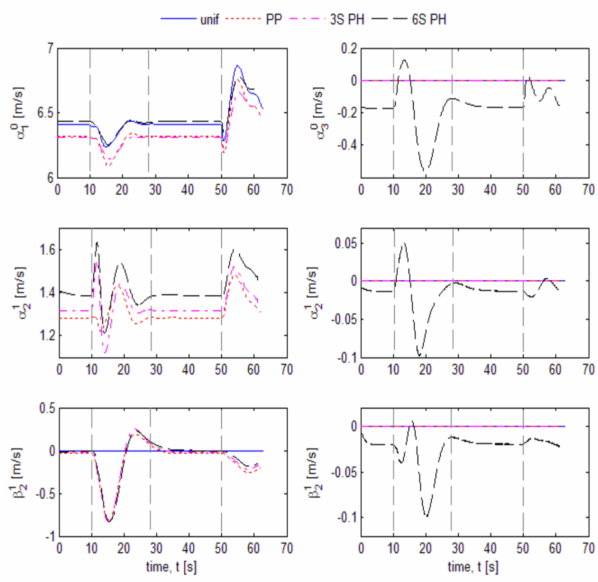

Figure 7: Main rotor inflow components during approach to a ship deck in sea state 6 using different inflow models

The effect of an increasing wave height on control input has been investigated by comparing results for the assumed four sea states 1, 4, 6 and 9, using the six state Peters-He model with dynamic ground effect model. Figure 10 presents the required control inputs, showing that while the heaving motion is affecting the collective control workload, both longitudinal and cyclic controls are hardly influenced. These results are directly related to the effect that the moving platform has on the rotor inflow components, as depicted in Figure 11. The lateral and longitudinal components show only small fluctuations when increasing sea state number, whereas the fluctuations of the two uniform components have a gradually increasing amplitude.

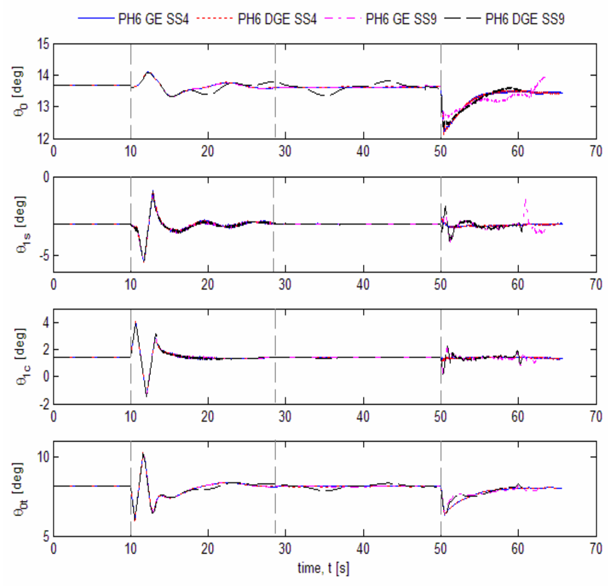

Figure 8: Effect of ship's heaving motion on control inputs, for a six-state Peters-He model using a static and a dynamic ground effect model

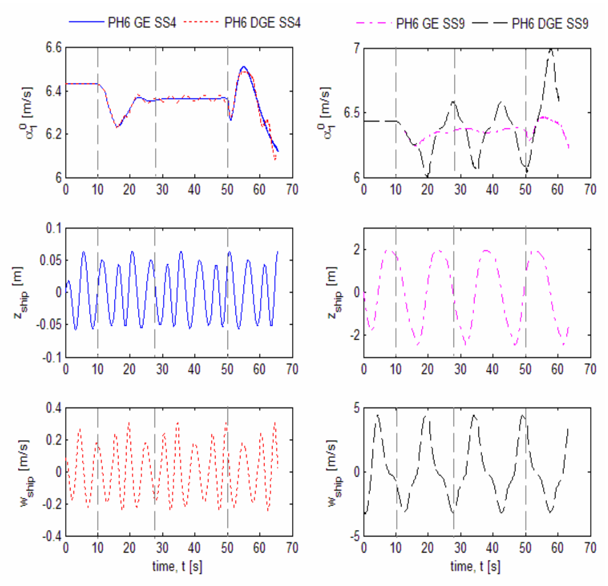

Figure 9: Effect of ship's heaving motion on uniform inflow, for a six-state Peters-He model using a static and a dynamic ground effect model

The combined PD and PID controller is able to fly the approach for all sea states, showing a almost linear decrease in absolute landing accuracy above sea state 4, as depicted in Figure 12. Only small corrections to the gain values are required.

Comparing the results for all test cases, it becomes clear that the ground effect does have an impact on pilot workload, especially the collective control. For increasing sea state, the amplitude of the required input increases gradually, due to fluctuations in the uniform inflow. From Figure 10 one can see that the cyclic controls are hardly affected. Furthermore, the differences between the results for the three and six-state Peters-He model are negligible small.

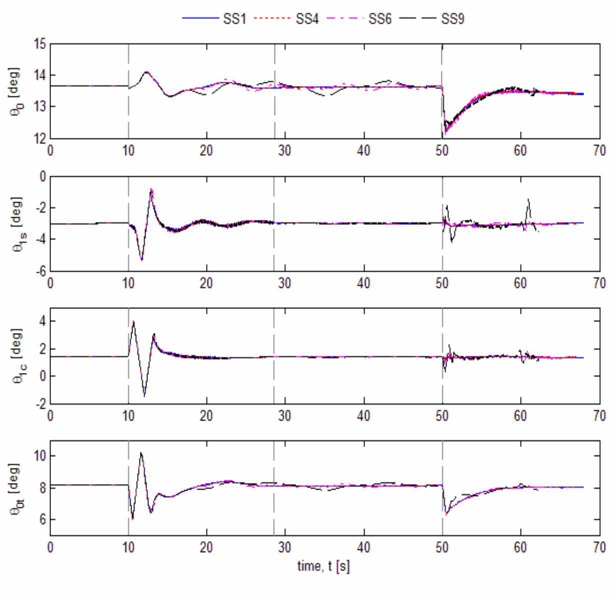

Figure 10: Control angles during approach to a ship deck, for different sea states

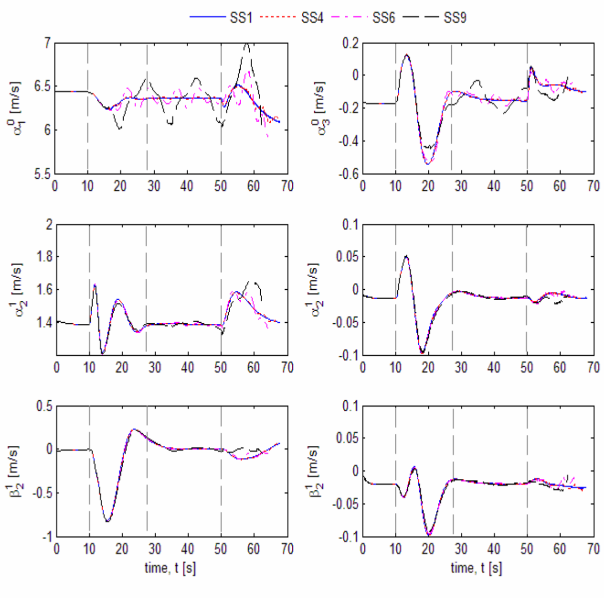

Figure 11: Main rotor inflow components during approach to a ship deck, for different sea states

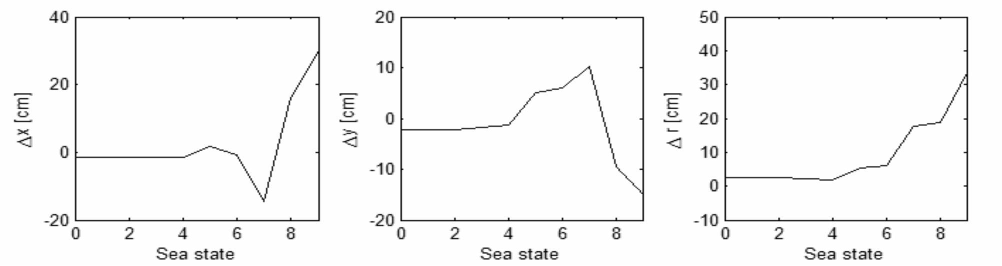

Figure 12: Landing position accuracy for increasing sea state

4. CONCLUSIONS

The present paper has presented the enhancements made to the simulation tool *Helix* to increase the fidelity in the simulation of helicopter/ship operations. A three and six-state Peters-He inflow model has been implemented, together with a model capable of representing the effect of the proximity a finite-width platform.

Exemplary for the application of *Helix*, a combination of a classical PD and PID controller has been used to simulate a fore/aft approach with an IAR-330 Puma SOCAT helicopter to a Type 22 frigate. The ship's motion was modeled by using the processed output of the "Ship Motion Program". For different sea states, the effect of inflow model and ground effect model fidelity on pilot workload has been investigated, showing an increase in collective control workload, closely related to the ship's heaving velocity.

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