

DEVELOPMENT OF A 6 DOF NONLINEAR HELICOPTER MODEL FOR THE MPI CYBERMOTION SIMULATOR

Carlo A. Gerboni,^{1,2} Stefano Geluardi,^{1,2} Mario Olivari,^{1,2} Frank M. Nieuwenhuizen,¹
Heinrich H. Bühlhoff,¹ and Lorenzo Pollini²

¹*Max Planck Institute for Biological Cybernetics*
Spemannstrasse 38, 72076 Tübingen
Germany

²*University of Pisa*
Via Diotisalvi 2, 56122 Pisa
Italy

Email: {carlo.gerboni; stefano.geluardi; mario.olivari}@tuebingen.mpg.de
{frank.nieuwenhuizen; heinrich.buelthoff}@tuebingen.mpg.de
lpollini@dsea.unipi.it

Abstract

This paper describes the different phases of realizing and validating a helicopter model for the MPI CyberMotion Simulator (CMS). The considered helicopter is a UH-60 Black Hawk. The helicopter model was developed based on equations and parameters available in literature. First, the validity of the model was assessed by performing tests based on ADS-33E-PRF criteria using closed loop controllers and with a non-expert pilot. Results on simulated data were similar to results obtained with the real helicopter. Second, the validity of the model was assessed with a helicopter pilot in-the-loop in both a fixed-base simulator and the CMS. The pilot performed a vertical remask maneuver defined in ADS-33E-PRF. Most metrics for performance were reached adequately with both simulators. The motion cues in the CMS allowed for improvements in some of the metrics. The pilot was also asked to give a subjective evaluation of the model by answering the Israel Aircraft Industries Pilot Rating Scale (IAI PRS). Similarly to results of ADS-33E-PRF, pilot responses confirmed that the motion cues provided more realistic flight experience.

NOTATION

| | | | |
|-----------------|---|--------------------------|---|
| | | k_1, k_2, k_3, k_4 | augmentation system parameters (-) |
| a_0 | main rotor blade lift curve slope ($1/rad$) | C_T | rotor thrust coefficient (-) |
| s | rotor solidity (-) | I_{xx}, I_{yy}, I_{zz} | moments of inertia of the helicopter about the x-,y-,z-axes ($kg \cdot m^2$) |
| u, v, w | translational velocity components of helicopter along fuselage x-,y-,z-axes (m/s) | M_a | helicopter mass (kg) |
| p, q, r | angular velocity components of helicopter along fuselage x-,y-,z-axes (rad/s) | R | main rotor radius (m) |
| | | S_E | area of the empennage components (fin or tail plane) or of the fuselage (m^2) |
| p_w, q_w, r_w | angular velocity components of helicopter in hub axes (rad/s). With a bar they are normalized by Ω | | |

| | |
|---|--|
| T | main rotor thrust (N) |
| V | forward velocity (m/s) |
| V_E | total velocity incident on empennage components (on fin or on tail plane) or on fuselage (m/s) |
| θ, ϕ, ψ | Euler angles defining the orientation of the aircraft relative to the Earth (rad) |
| $\beta_0, \beta_{1c}, \beta_{1s}$ | rotor blade coning, longitudinal and lateral flapping angles (rad) |
| β_{1cw}, β_{1sw} | longitudinal and lateral pitch angle in hub axes (rad) |
| $\lambda_0, \lambda_{1c}, \lambda_{1s}$ | rotor uniform and first harmonic inflow velocities (normalized by ΩR) |
| θ_0 | collective pitch angle (rad) |
| θ_{1c}, θ_{1s} | lateral and longitudinal pitch angle (rad) |
| $\theta_{1cw}, \theta_{1sw}$ | lateral and longitudinal pitch angle in hub axes (rad) |
| θ_{0T} | tail rotor collective pitch angle (rad) |
| θ_{tw} | main rotor blade linear twist (rad) |
| $\eta_0, \eta_{1c}, \eta_{1s}$ | collective lever and cyclic stick position (normalized by the stick deflection range) |
| γ | Lock number ($-$) |
| ρ | air density (kg/m^3) |
| μ | advance ratio ($V/(\Omega R)$) |
| μ_z | velocity of the rotor hub in hub/shaft axes (normalized by ΩR) |
| Ω | main rotor speed (rad/s) |

1. INTRODUCTION

An investigation on how to make a Personal Air Vehicle (PAV) as easy to fly as driving a car is currently conducted at the Max Planck Institute for Biological Cybernetics, under the myCopter EU funded research program.^[1] In these studies, rotorcraft vehicles are considered as the main reference since their dynamics and kinematics best reflect those of a PAV. A key

facility that is essential for these studies is the MPI's Cybermotion Simulator (CMS) shown in Figure 1. The CMS is an anthropomorphic robot with eight degrees of freedom and a cabin as end-effector capable of hosting a person. The cabin is equipped with a stereo projection system. A 10 meters linear track allows to increase the workspace of the robot. Different vehicle dynamics models can be simulated in its large motion envelope.

So far, experiments related to helicopter models were already performed on the CMS but only with simplified dynamics.^[2] However, recent studies at the MPI led to considering implementing a more complex and realistic helicopter model. These studies consist of the development of new human-machine interface technologies,^[3] investigation of pilots behavior, training of non-expert pilots, implementation of new control systems to be tested in simulation with human in-the-loop and training of pilots for performing specific maneuvers for system identification purposes.^[4] Therefore, it was decided to implement a full-flight nonlinear dynamic helicopter model to be used in the CMS.

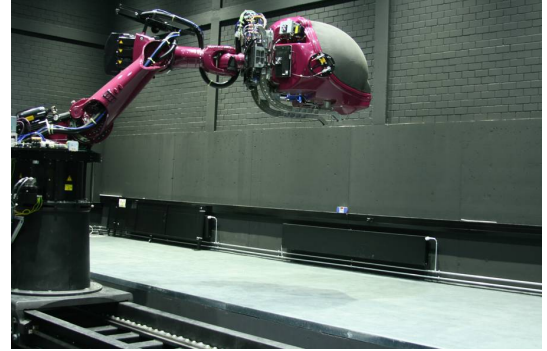


Figure 1: The 8 DoF MPI CyberMotion Simulator (<http://www.cyberneum.de/>).

Nonlinear models for unmanned small-size helicopters have been investigated and tested in literature.^[5] On the contrary, nonlinear models for full-size helicopters are not very common, due to the difficulty of accurately implementing the components of the vehicle and obtaining reliable aerodynamic parameters. Few nonlinear helicopter models have been developed and tested in motion simulators but they are not readily available.^[6, 7]

This paper presents the main steps considered for developing a mathematical helicopter model for use in the CMS. The complexity of the implemented model and the large motion envelope of the simulator should allow for simulating highly realistic flight scenarios. As first step, the model was implemented and validated by performing several test maneuvers with the help of closed-loop controllers. After that, a helicopter pilot

was asked to evaluate the model in a fixed-base simulator. Finally, the same pilot evaluated the model in the CMS.

The paper is organized as follows: Section 2 describes the development of the model. Section 3 presents the results of the time and frequency domain analysis done on the model. Section 4 is dedicated to the experiments with the helicopter pilot in the fixed-base simulator and in the CMS. Finally, future steps are summarized.

2. MODEL DEVELOPMENT

A 6 Degrees of Freedom (DoF) nonlinear mathematical model was built based on generic helicopter dynamics equations.^[8] As shown in Figure 2, the helicopter model is composed of five subsystems that represent the main helicopter components: the main rotor, the tail rotor, the fuselage, the empennage and the transfer functions from the pilot input to the blades of the two rotors (flight control system). The main rotor speed was assumed constant. In addition, the reaction of the ground was modeled as a mass-spring-damper system.

The outputs of every subsystem are forces and torques in body frame of reference, from which linear and rotational accelerations are obtained. Then, the Euler angles are calculated to define the attitude of the helicopter.

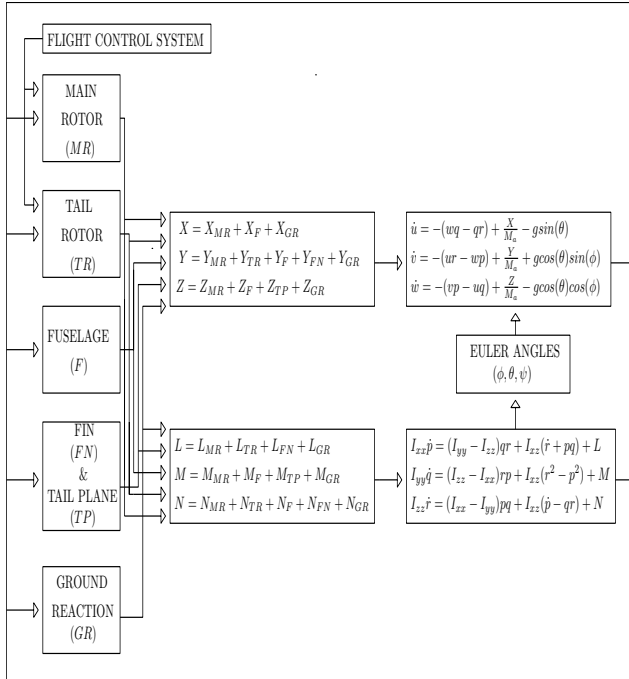


Figure 2: Block diagram of the helicopter model and reaction of the ground

The resulting dynamic system has the form

$$(1) \quad \dot{\mathbf{x}} = \mathbf{F}\{\mathbf{x}, \mathbf{u}, t\}$$

where the state vector \mathbf{x} has the following elements:

$$(2) \quad \mathbf{x} = \{\mathbf{x}_f, \mathbf{x}_r, \mathbf{x}_b\}$$

in which the subscripts f, r, b refer to the fuselage, the rotors and the blades, respectively. The components of the states \mathbf{x}_f , \mathbf{x}_r and \mathbf{x}_b are:

$$(3) \quad \mathbf{x}_f = \{u, v, w, p, q, r, \phi, \theta, \psi\}$$

$$(4) \quad \mathbf{x}_r = \{\beta_0, \beta_{1c}, \beta_{1s}, \lambda_0, \lambda_{1c}, \lambda_{1s}\}$$

$$(5) \quad \mathbf{x}_b = \{\theta_0, \theta_{1c}, \theta_{1s}, \theta_{0T}\}$$

with all the components defined in the nomenclature. The vector \mathbf{u} represents the pilot inputs:

$$(6) \quad \mathbf{u} = \{\eta_0, \eta_{1s}, \eta_{1c}, \eta_{0T}\}$$

where η_0 is the *collective* lever displacement, η_{1s} the *longitudinal cyclic* stick, η_{1c} is the *lateral cyclic* stick and η_{0T} is the displacement of the *pedals*.

The helicopter chosen for this work is the UH-60 Black Hawk because it is one of the most described in literature. The mechanical, dynamic and aerodynamic parameters were mainly taken from two sources.^[9, 10] The dynamic equations of the model are not repeated here as they are described in detail in literature.^[8] Only several aspects of the model implementation that received particular attention are detailed in the following sections.

2.1. Rotors

Two main parameters of the main and the tail rotor are the *thrust coefficient* C_T and the *total inflow* λ_0 passing through the blades. We employed a rather complete model that, although valid only at steady state, can model several aerodynamic effects. The thrust coefficient and the total inflow equations are:

$$(7) \quad C_T = \frac{a_0 s}{2} \left(\theta_0 \left(\frac{1}{3} + \frac{\mu^2}{2} \right) + \frac{a_0 s}{2} \left(\frac{\mu}{2} \left(\theta_{1sw} + \frac{p_w}{2} \right) + \frac{a_0 s}{2} \left(\frac{\mu_z - \lambda_0}{2} \right) + \frac{a_0 s}{2} \left(\frac{1}{4} (1 + \mu^2) \theta_{tw} \right) \right)$$

$$(8) \quad \lambda_0 = \frac{C_T}{2\sqrt{[\mu^2 + (\lambda_0 - \mu_z)^2]}}$$

The two parameters C_T and λ_0 depend on each other; this makes computing the flight condition complex. Different approaches have been proposed to calculate the solution of equations 7 and 8. For instance, a closed-form solution for C_T and λ_0 can be found for each specific flight condition (take off, hover, forward flight and landing).^[8] However, this approach implies switching between different sets of equations when simulating the model in different steady states. Hence, an iterative solution based on a Newton-Raphson method was applied to arrive at a model that is valid in all flight conditions.

Another issue we encountered during the development was the relation between the blade pitch angles and the displacement of the swashplate. Different models [8, 12, 13] were tested in order to find the relationship that better approximate the response of the real helicopter.^[14] Best accuracy was obtained with a method that reduce much the effect of the blade linear twist θ_{tw} , that in helicopter like the UH-60 has an important influence due to its big value.^[13]

$$\beta_0 = \gamma \left[\frac{\theta_0}{8}(1 + \mu^2) + \frac{\theta_{tw}}{10}(1 + \frac{5}{6}\mu^2) + \frac{\mu}{6}\theta_{1sw} - \frac{\lambda_0}{6} \right] \quad (9)$$

$$\beta_{1sw} = \theta_{1cw} + \frac{(-\frac{4}{3}\mu\beta_0)}{(1 + \frac{1}{2}\mu^2)} \quad (10)$$

$$\beta_{1cw} = -\theta_{1sw} + \frac{-\frac{8}{3}\mu[\theta_0 - \frac{3}{4}\lambda_0 + \frac{3}{4}\mu\theta_{1sw} + \frac{3}{4}\theta_{tw}]}{1 - \frac{1}{2}\mu^2} \quad (11)$$

2.2. Aerodynamics of fuselage and empennage

Aerodynamic equations for fuselage and empennage generally change between different steady states and different helicopters. Data from wind tunnel tests in each steady state are necessary for describing the evolution of these equations. Our approach consisted of implementing generic equations that could also be used for other helicopters than the UH-60 considered in this paper. The generic equations for drag is given as:

$$\frac{1}{2}\rho V_E^2 S_E C_{Efriction} \quad (E \in \{fin, tailplane, fuselage\}) \quad (12)$$

The *friction coefficient* $C_{Efriction}$ is defined differently for the fuselage and for the empennage. For the fuselage it is derived from table look-up functions made with generalized aerodynamic coefficients.^[8] For the empennage it is defined as

$$C_{Efriction} = \begin{cases} k \sin(\alpha) & : |C_{friction}| < \delta \\ -\delta * \text{sgn}(\sin(\alpha)) & : |C_{friction}| > \delta \end{cases} \quad (13)$$

in which α is the angle of incidence of the air with the tail plane and with the fin. In this model, the limit factor δ and the scaling factor k are taken by approximated wind tunnel equations of the empennage.^[9, 10] This was done for this helicopter because a detailed report is present in literature.^[10] However, these variables can also be tuned manually or with the help of an experienced pilot.

2.3. Stability Augmentation System

The model input vector is composed of the four controls (collective, lateral and longitudinal cyclic and pedals). The pilot changes the blade pitch described in (5) by moving the controls.

The UH-60 features a *Stability Augmentation System* (SAS) that is used to aid the pilot. We only considered such a system for the cyclic controls, as these are considered most difficult to use. The transfer functions that connect the cyclic input of the pilot with the main rotor blade pitch are

$$\theta_{1c} = \frac{(a_1 \eta_{1c} + b_1) + k_1 p + k_2 \phi}{1 + \tau s} \quad (14)$$

$$\theta_{1s} = \frac{(a_2 \eta_{1s} + b_2) + k_3 q + k_4 \theta}{1 + \tau s} \quad (15)$$

In which (a_1, a_2) and (b_1, b_2) define the angular ranges for θ_{1c} and θ_{1s} . (k_1, k_2, k_3, k_4) are the parameters of the SAS. The SAS parameters are tuned to obtain frequency responses similar to the real helicopter as it was active during all the tests.^[15] At the same time the contribution of the SAS is saturated in such a way that physical limits of the blades are not exceeded.

3. VALIDATION WITH CLOSED-LOOP CONTROLLERS

This section presents validation tests performed with closed-loop controllers such that the tests can be performed without an experienced pilot. Different analyses were performed that cover different aspects of a helicopter model. Two tests will be presented that were performed in the time and frequency domain. The results were compared with flight test data from literature. All simulations were done with MATLAB/Simulink and a basic virtual environment

developed in Unity3D.

By definition the *Aeronautical Design Standard* (ADS-33E-PRF) defines the *desired Handling Qualities for military helicopters*.^[16] The ADS-33E-PRF tests can be divided in two groups: quantitative tests and MTEs (*Mission Task Elements*). The quantitative tests requires giving a specific input (i.e. steps and sweeping sinusoids) and evaluating the responses of the rotorcraft in the time and frequency domain. MTEs are composed of specific maneuvers that a pilot needs to accomplish while respecting some performance metrics. This section describes the quantitative tests while the MTEs are detailed in Section 4.

3.1. Helicopter in hover with controllers

To control the helicopter in hover condition, controllers were designed as *Proportional, Integral, Derivative* (PID) regulators. These controllers regulated the actual speed of the rotorcraft to a reference value by controlling the blade pitch angles. For the hover condition, all the reference velocities were set to zero. Table 1 presents the blade pitch of the model compared with results from flight tests.^[14] The comparison shows that the collective and the longitudinal pitch are almost the same while the lateral pitch has a little difference. From this first simulation, it was shown that trimming the model in hover resulted in similar responses of the blades compared to a flight test.

Table 1: Blade pitch angles in hover (angles are given in degrees)

| | Flight test ^[14] | Model |
|---------------|-----------------------------|--------------|
| θ_0 | $\simeq 8$ | $\simeq 8$ |
| θ_{1c} | $\simeq 3.5$ | $\simeq 1.5$ |
| θ_{1s} | $\simeq -3.5$ | $\simeq -3$ |

3.2. Attitude quickness test

The first quantitative test is the *attitude quickness response*. The aim of this test is to study the quickness of the rotorcraft at changing its attitude in response to a step input. The evaluated metrics are

$$(16) \quad \text{roll attitude quickness} = \frac{p_{pk}}{\Delta\phi}$$

$$(17) \quad \text{pitch attitude quickness} = \frac{q_{pk}}{\Delta\theta}$$

The parameters p_{pk} , q_{pk} , $\Delta\phi$ and $\Delta\theta$ are highlighted in Figure 3.

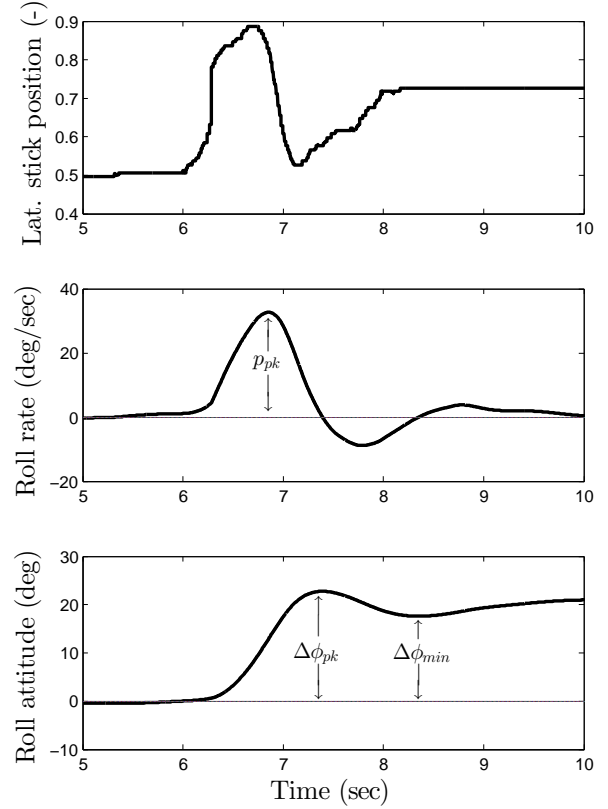


Figure 3: Lateral cyclic input for roll attitude quickness. Parameters involved in the test are highlighted. The range of the cyclic stick is between 0 and 1

To compare results of our model with those obtained with a real helicopter, we replicated the same pilot input^[15] with a joystick to have a left and right roll, and a forward and backward pitch while controlling the other axes in hover with the PID controllers. The small duration of the input and the use of the PID controllers for the other axes allowed performing this task without an experienced pilot.

Figure 4 and 5 show the results of the attitude quickness test compared with real data.^[15] The quickness of the model with respect to the data of a flight test is almost identical. This shows that the model reaches Level 1 Handling Qualities.

3.3. Frequency response analysis

The second analysis performed is based on the frequency response of the system. The main parameters of interest are the bandwidth of the system and the phase delay. The first parameter is defined by the frequency at which the phase is 135° while the phase delay is

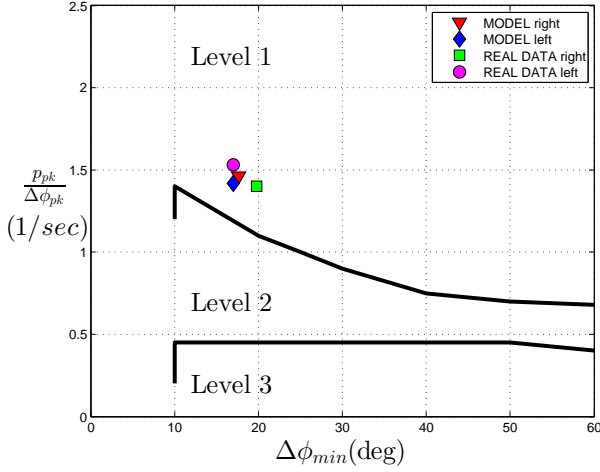


Figure 4: Roll attitude quickness test

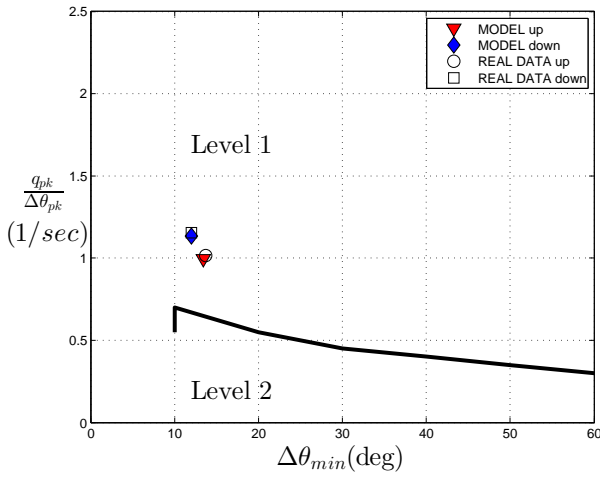


Figure 5: Pitch attitude quickness test

$$(18) \quad \tau_p = \frac{\Delta\Phi_{2\omega_{180}}}{57.3 \times 2\omega_{180}}$$

in which $2\omega_{180}$ indicates two times the frequency at which the phase is 180° while $\Delta\Phi_{2\omega_{180}}$ is the phase difference between ω_{180} and $2\omega_{180}$.^[8] At the Max Planck Institute for Biological Cybernetics studies of rotorcraft identification are conducted^[17] based on a method developed in literature.^[18] Using this work, the frequency responses of the model were obtained for the roll, pitch and yaw degrees of freedom with the helicopter in hover. A small amplitude sweeping sinusoid signal was given as input for the DoF of interest and the corresponding Euler angle was considered as output. The Bode diagrams for roll, pitch and yaw are shown in Figure 6, in Figure 7 and in Figure 8, respectively and the parameters required for equation 18 are highlighted.

The phase delay results are given in Figures 9, 10 and 11. Two different observations can be made from

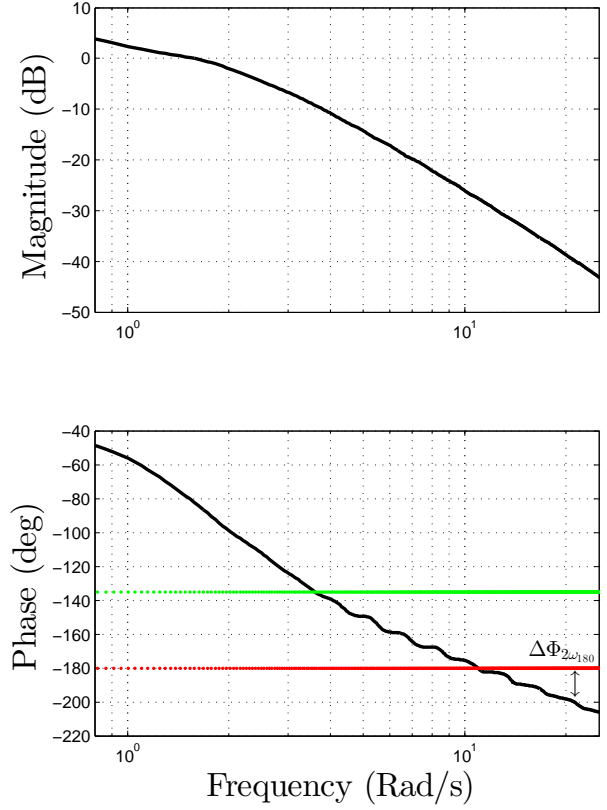


Figure 6: Bode diagram for the roll channel

the results: the bandwidth of the identified system is almost the same of the real vehicle for all three channels. However, the roll and pitch responses show a different phase delay caused by a smaller $\Delta\Phi_{2\omega_{180}}$ of the model compared with the real system at high frequencies. The causes for this effect are currently under investigation.

4. VALIDATION WITH A HELICOPTER PILOT

The tests described in the previous section showed the similarity of the model with the real helicopter. In the second step, the model was tested with a helicopter pilot. The tests were done in fixed-base simulator and a motion simulator. The same maneuver was performed in both simulators. The pilot was instructed maintain the performance levels defined in the ADS-33E-PRF criteria as best as possible during the maneuver task.

4.1. Experimental setups

The first evaluation with the pilot was executed in a fixed-base simulator. The simulation was executed with a real-time pc. A complex virtual environment

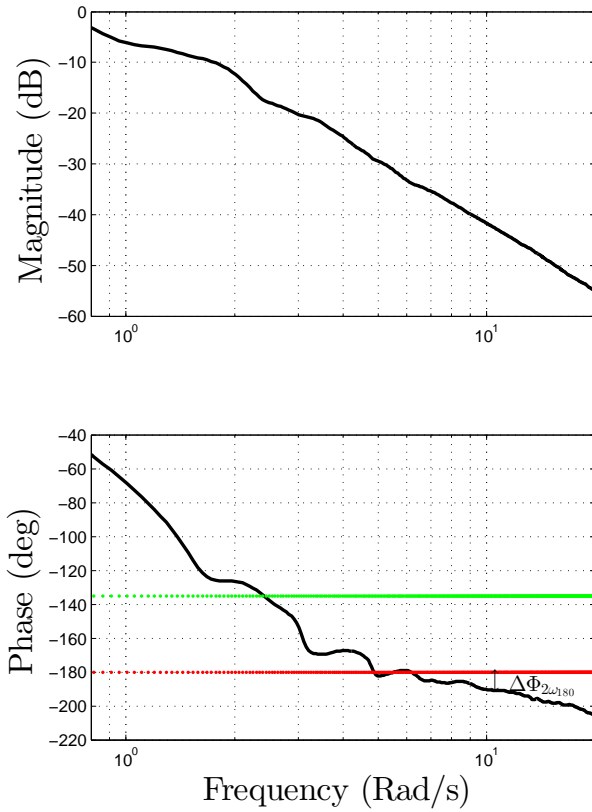


Figure 7: Bode diagram for the pitch channel

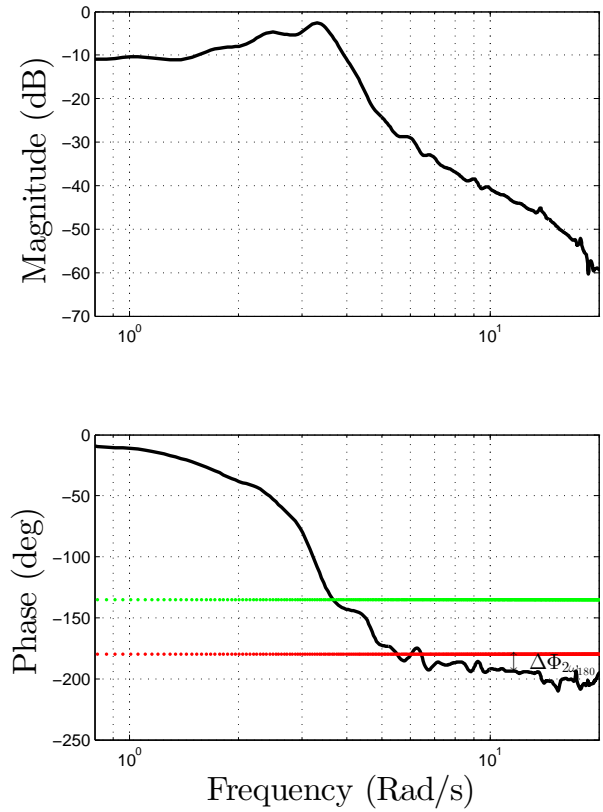


Figure 8: Bode diagram for the yaw channel

was developed in Unity3D, which was composed of an airport with markers that were required to execute the maneuver. A control-loaded cyclic stick, collective level and pedals were used (Wittenstein GmbH, Germany), see Figure 12.

The experiment was performed with a screen with a field of view of 230 deg horizontal and 125 deg vertical, see Figure 13.

The second evaluation was performed in the MPI CyberMotion Simulator (CMS), see Figure 1. This simulator is a 8 DoF serial anthropomorphic robot with an enclosed cabin. The same control-loaded input devices were used as in the fixed-base simulator and the same virtual environment was shown to the pilot. The linear accelerations and rotational velocities from the model were scaled by multiplication with factors between 0.01 and 0.9. Washout filters are not used. The scaling was relatively strong as the main purpose of this test was to validate the model, and not to optimize the motion cues presented to the pilot.

4.2. Description of the task

The evaluation was divided in two sequential parts. The first part was executed only in the Panolab while

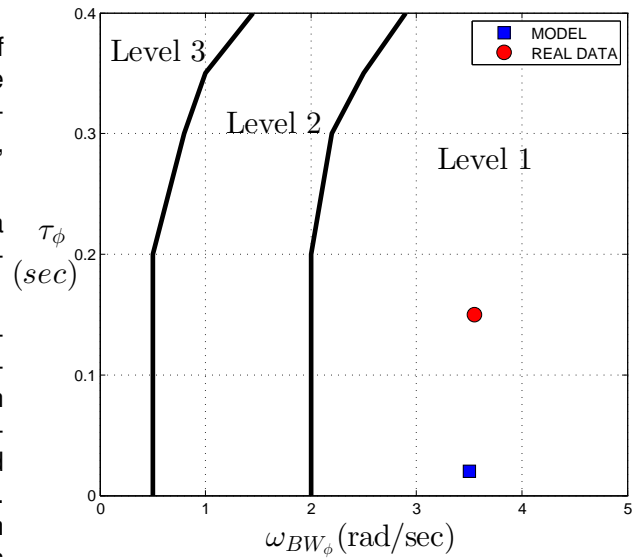


Figure 9: Roll frequency response analysis

the second was executed in both simulators. In the first part the pilot tested four different flight conditions to rate the responses of the model. In the second part he performed a specific ADS-33E-PRF MTE.

The virtual environment used for both parts is shown in Figure 14. Three squares in the ground, a bar

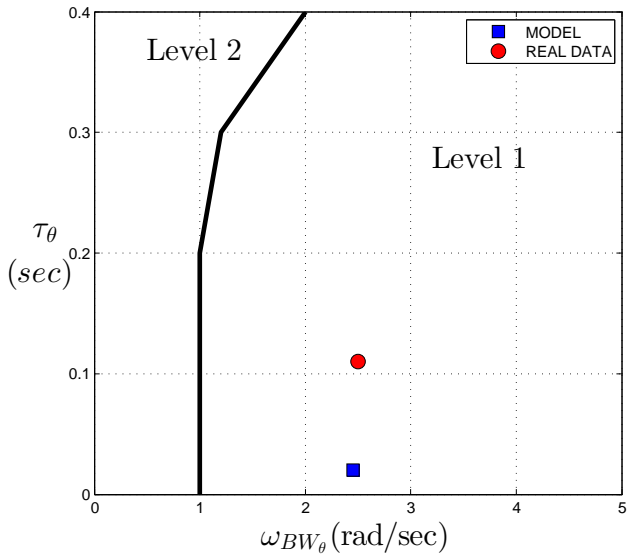


Figure 10: Pitch frequency response analysis

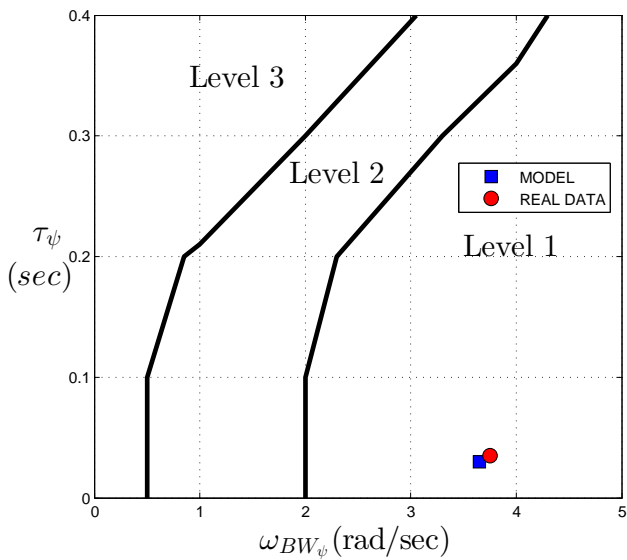


Figure 11: Yaw frequency response analysis

with two spheres in the starting position and different markers between the squares are present in the environment. These elements are collocated in such a way different MTEs can be executed and the markers limit the displacements allowed to consider the required performances reached.

The goal of the first part was to check all the 6 DoF of the rotorcraft using all the four inputs. This means that in this phase no attention was paid in execution time and to distance from the markers position.

In details the four maneuvers were:

1. Take-off along the bar shown in Figure 14 and hover in front of the higher sphere. Subsequently a vertical descent and a new hover in front of the

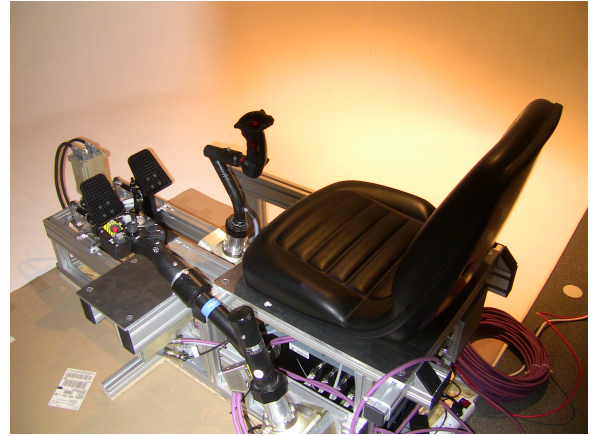


Figure 12: Control loaded cyclic stick, collective lever and pedals used in the experiments

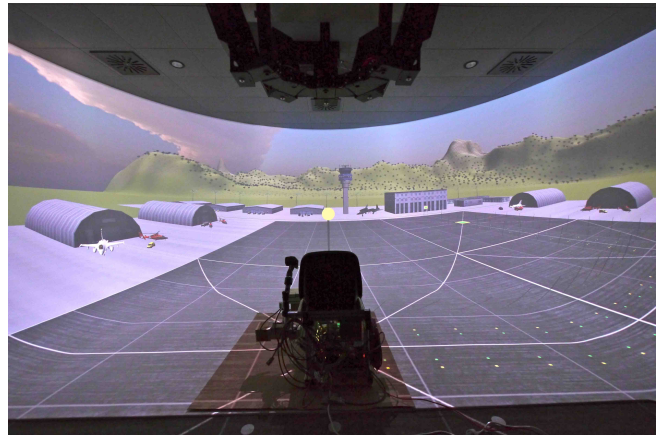


Figure 13: Experimental setup
(<http://www.cyberneum.de/research-facilities/panolab>)

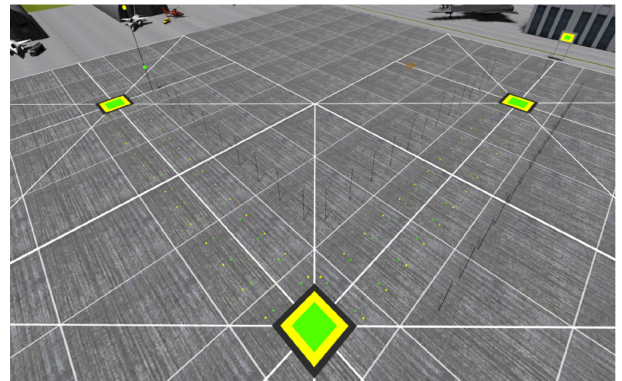


Figure 14: Unity3D visualization used for the simulator evaluations. The starting position is on the left-most.

lower sphere.

2. A right lateral displacement from the starting square on the ground to the second square and

back again.

3. Forward flight from the second square to the third and back again.
4. A 360° turn around the bar.

After each maneuver, the pilot rating scale (PRS) was used by the pilot to assess the model. This PRS asks the pilot to evaluate the primary response and the secondary response of each executed maneuver. As an example, for the maneuver 1, the primary response is given by the use of the collective for the vertical movement, while the secondary response is the compensatory action that the pilot does with the pedals to counteract the yaw motion. In addition he is asked to rate the difficulties in executing the maneuver in relation to the response of the model and with the visualization.

The second part is the execution of a specific MTE.^[16] The maneuver chosen is the vertical remark. This maneuver is composed of three parts:

1. The maneuver starts with a vertical remark from a stabilized hover at 75 ft to an altitude of 35 ft (slightly modified from the original maneuver ^[16])
2. Lateral displacement of 300 ft
3. Stabilize in a new hover position

This maneuver was chosen for several reasons. First of all it covers different flight conditions: the initial take off to reach the first hover position where the maneuver starts, the vertical descent and the fast lateral displacement. Second with this maneuver it is possible to use all the inputs of the system: the pedals are used to counteract turns during the displacement, the lateral cyclic for the lateral displacement, the longitudinal cyclic for maintaining the longitudinal position and the collective to maintain altitude. Third, with the lateral displacement is possible to exploit the linear track of the CMS for a more realistic reproduction of lateral accelerations. The markers placed in the environment indicate the adequate or desired performance as defined in ADS-33E-PRF for both conditions.

The pilot that performed the test has experience with real helicopters and with simulators. He has about 110 flight hours with around 700 take offs and landings. For the simulators he flew a Bell UH-1D in different sessions.

4.3. Dependent measures

As the nonlinear dynamic helicopter model described in this paper is intended to be used to investigate pi-

lots behavior, to record data for system identification purposes and to test new control systems to use with human in-the-loop, it is necessary to show that the model can be used to perform complex tasks. Therefore, more attention was given to some of the metrics as defined in ADS-33E-PRF ^[16] because they are independent from possible visualization difficulties. These metrics are

1. Maintain altitude after remark and during displacement within +10 ft and -15 ft (± 10 ft to be desired)
2. Maintain heading within ± 15 deg (10 deg to be desired)
3. Achieve the final stabilized hover within 25 sec of initiating the maneuver (15 sec to be desired)

4.4. Results

The *Israel Aircraft Industries Pilot Rating Scale* (IAI PRS),^[18] rates the primary and the secondary helicopter responses with a scale from 0 to 6. In this scale 0 means that the response cannot be evaluated while 6 means an exact match of the model response with the real helicopter. The difficulty of execution scale, which includes the stability characteristics dissimilarities and the simulation difficulties, ranges from 0 to 5 where again 0 means that is not possible to evaluate and 5 that there is an exact matching. Table 2 shows the ratings given by the pilot.

Table 2: Pilot evaluation

| | Prim. res. | Sec. res. | Difficulty of exec. |
|--------------|------------|-----------|---------------------|
| <i>Man.1</i> | 3.6 | 3.5 | 3.5 |
| <i>Man.2</i> | 3 | 3.5 | 2.5 |
| <i>Man.3</i> | 3.8 | 3.8 | 2.5 |
| <i>Man.4</i> | 4 | 4 | 4 |

Apart from the ratings, verbal comments of the pilot were recorded:

"Optimal coupling between collective and pedals"

"The lack of motion makes it difficult to maintain altitude during lateral or longitudinal displacement"

"The overall evaluation is very good."

A consideration from the pilot's remarks was that the lack of motion made it difficult to fly the helicopter model. The main problem was to maintain altitude due to the fact that in the real helicopter the pilot

"feels" the movement more than he can see the movement. So we expected an improvement of the performance with a motion simulator. Table 3 shows performances reached for both simulators:

Table 3: Performances in the two simulators

| | Panolab | CMS |
|----------|-------------------|-------------------|
| Metric 1 | <i>Adequate</i> | <i>Desired</i> |
| Metric 2 | <i>Desired</i> | <i>Desired</i> |
| Metric 3 | <i>NotReached</i> | <i>NotReached</i> |

As expected there was an improvement of the first metric. Figure 15 highlights the vertical position during lateral displacement.

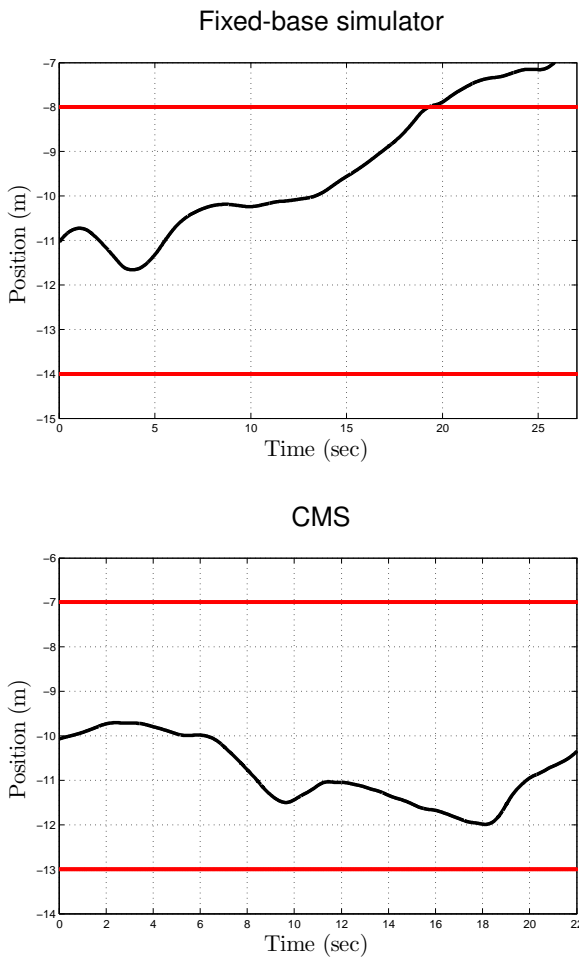


Figure 15: Vertical position in the two simulators during lateral displacement

The first problem caused by the lack of motion in the fixed-base simulator was the difficult to stop the vertical descend in front of the lower sphere. The second and most important problem was the continuous descent during all the lateral displacement. This resulted in adequate performance. Both these problems

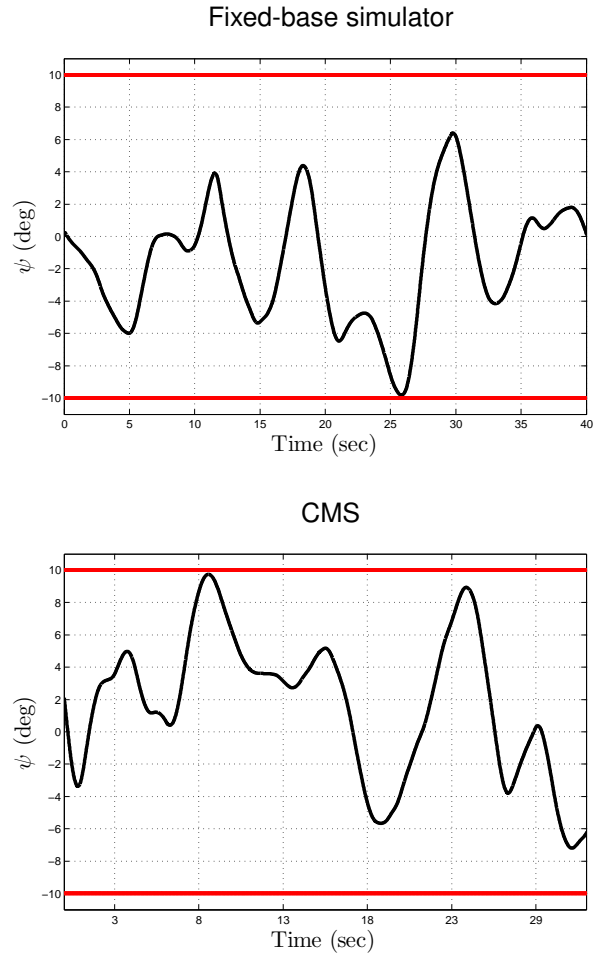


Figure 16: Yaw Euler angle during the entire maneuver

were not present in the CMS where the pilot stopped exactly in front of the lower sphere and stayed well within the performance bounds. In the motion simulator the performance was reached in a desired way.

Heading was maintained in a desired way in both simulators. Figure 16 shows the results.

The time of execution of the entire maneuver was of 35 seconds in the fixed-base simulator and of 31 seconds in the CMS. Since the performance is considered adequate if executed in 25 second, none of the two maneuvers was satisfactory. However the improvement obtained in the CMS suggests that with more training and better motion cueing might make it possible to reach this metric too.

5. CONCLUSIONS

This paper has presented the development and the validation of a fully non-linear helicopter model. The implementation of the model was briefly described.

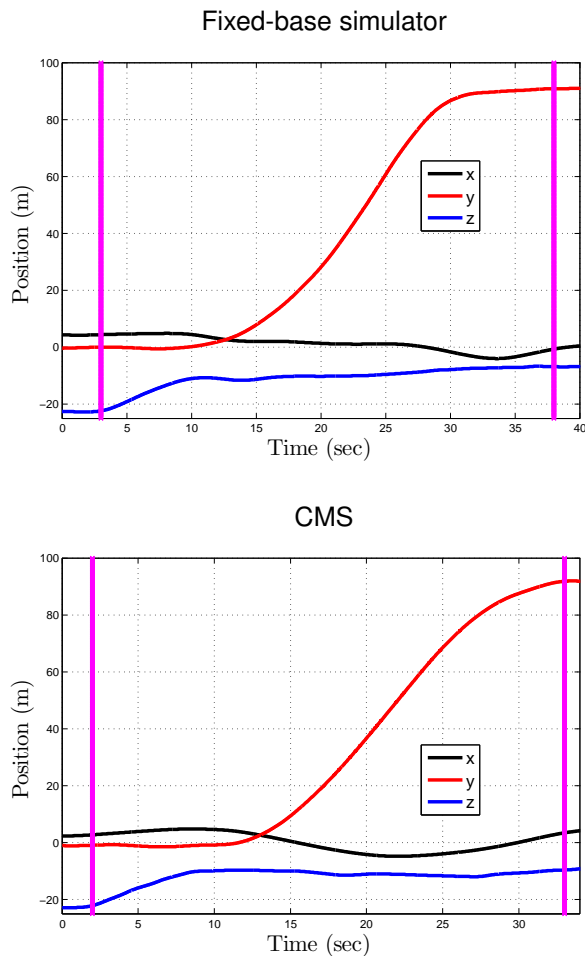


Figure 17: Inertial position along x-,y-,z-axes during the vertical remask maneuver. Two vertical lines indicate when the maneuver starts and when ends

Different kind of tests were done to validate the implemented model. Time and frequency domain tests showed the correctness of the implementation. Furthermore, validation measurements were performed on a fixed-base simulator and a motion simulator which showed favourable results.

Future steps involve further improvements to the model and the use of more pilots for testing. Moreover different MTEs will be tested to really understand the ability of the model to be used as a real helicopter.

ACKNOWLEDGEMENTS

Frank M. Nieuwenhuizen was supported by the myCopter project, funded by the European Commission under the 7th Framework Program (<http://www.mycopter.eu>).

REFERENCES

- [1] Nieuwenhuizen, F. M., Jump, M., Perfect, P., White, M., Padfield, G., Floreano, D., Schill, F., Zufferey, J., Fua, P., Bouabdallah, S., Siegwart, R., Meyer, S., Schippl, J., Decker, M., Gursky, B., Hfinger, M., and Bühlhoff, H. H., "myCopter: Enabling Technologies for Personal Aerial Transportation Systems," *3rd International HELI World Conference, Frankfurt/Main*, 2011.
- [2] Drop, F. M., Pool, D. M., van Paassan, M. M., Mulder, M., and Bühlhoff, H. H., "Feedforward and Feedback Control Behaviour in Helicopter Pilots during a Lateral Reposition Task," *AHS 69th Annual Forum, Phoenix, USA*, 21-23 May 2013.
- [3] Olivari, M., Nieuwenhuizen, F. M., Bühlhoff, H. H., and Pollini, L., "Pilot Adaptation to Different Classes of Haptic Aids in Tracking Tasks," *Journal of Guidance, Control, and Dynamics*.
- [4] Geluardi, S., Nieuwenhuizen, F. M., Pollini, L., and Bühlhoff, H. H., "Data Collection for Developing a Dynamic Model of a Light Helicopter," *39th European Rotorcraft Forum, Moscow, Russia*, 3-6 September 2013.
- [5] Gula, P. and Gorecki, T., "Design, Experiments and Development of a Polish Unmanned Helicopter ILX-27," *39th European Rotorcraft Forum, Moscow, Russia*, 3-6 September 2013.
- [6] Padfield, G. and White, M., "Flight simulation in academia HELIFLIGHT in its first year of operation at the University of Liverpool," *The Aeronautical Journal*, 2003.
- [7] Stroosma, O., van Paassen, R., and Mulder, M., "Using the SIMONA Research Simulator for Human-Machine Interaction Research," *AIAA Modeling and Simulation Technologies Conference and Exhibit*, August 11-14 2003.
- [8] Padfield, G. D., *Helicopter Flight Dynamics: The Theory and Application of Flying Qualities and Simulation Modelling Second Edition*, Blackwell Publishing, 2007.
- [9] Hilbert, K. B., "A Mathematical Model of the UH-60 Helicopter," *NASA TM-85890*, 1984.
- [10] Howlett, J. J., "UH-60A Black Hawk Engineering Simulation Program: Volume I - Mathematical Model," *NASA 166309*, 1981.
- [11] Dreier, M. E., *Introduction to helicopter and tiltrotor simulation*, AIAA Education Series, 2007.

- [12] Banks, C., "Lessons on Helicopter dynamic," (<http://www.aeroflight.com/papers/helicopter>).
- [13] Li, Y., "Principles of Helicopter Aerodynamic chapter 4," (<http://www.scribd.com/doc/48524322/Principles-of-Helicopter-Aerodynamics-Chapter-4>).
- [14] Bluman, J. E., *Reducing Trailing Edge Flap Deflection Requirements in Primary Control Through a Moveable Horizontal Tail*, Ph.D. thesis, The Pennsylvania State University, 2008.
- [15] Blanken, C. L., Arterburn, D. R., and Cicolani, L. S., "Evaluation of Aeronautical Design Standard-33 Using a UH-60 A Black Hawk," *AHS 55th Annual Forum, Montreal, Canada, 25-27 May 1999*.
- [16] Baskett, B. J., "Aeronautical Design Standard performance specification Handling Qualities requirements for military rotorcraft," Tech. rep., DTIC Document, 2000.
- [17] Geluardi, S., Nieuwenhuizen, F., Pollini, L., and Bülthoff, H. H., "Frequency Domain System Identification of a Light Helicopter in Hover," *AHS 70th Annual Forum, Montreal, Canada, 20-22 May 2014*.
- [18] Zivan, L. and Tischler, M. B., "Development of a Full Flight Envelope Helicopter Simulation Using System Identification," *Journal of the American Helicopter Society*, Vol. 55, No. 2.

COPYRIGHT STATEMENT

The authors confirm that they, and/or their company or organization, hold copyright on all of the original material included in this paper. The authors also confirm that they have obtained permission, from the copyright holder of any third party material included in this paper, to publish it as part of their paper. The authors confirm that they give permission, or have obtained permission from the copyright holder of this paper, for the publication and distribution of this paper as part of the ERF2014 proceedings or as individual offprints from the proceedings and for inclusion in a freely accessible web-based repository.