European Rotorcraft Forum

DEVELOPMENT OF A CIVIL LIGHT HELICOPTER FLIGHT SIMULATOR FOR PILOT TRAINING

Urs Kazenmaier [1,2], urs.kazenmaier@tuebingen.mpg.de
Carlo A. Gerboni [1,2], carlo.gerboni@tuebingen.mpg.de
Stefano Geluardi [1], stefano.geluardi@tuebingen.mpg.de
Mario Olivari [1], mario.olivari@tuebingen.mpg.de
Tobias Richter [2], tobias.richter@ifr.uni-stuttgart.de
Walter Fichter [2], fichter@ifr.uni-stuttgart.de
Heinrich H. Bülthoff [1], heinrich.buelthoff@tuebingen.mpg.de

[1] *Max Planck Institute for Biological Cybernetics, Tübingen, Germany*
[2] *University of Stuttgart - Flight Mechanics and Controls Lab, Stuttgart, Germany*

Abstract
This paper aims at defining the necessary characteristics to develop a reliable and cheap helicopter flight simulator that could be used in flight schools for pilot training. The main contribution is the definition of helicopter dynamics and model parameters that are necessary to reproduce those characteristics perceivable by a pilot in a simulated environment. From this analysis, a physical-based nonlinear helicopter model is implemented. The proposed model description allows helicopter flight characteristics to be modified by changing only few physical parameters, which are readily accessible. The helicopter model is integrated with commercially available off-the-shelf helicopter controls and a Virtual Reality headset to create a cheap fixed-based simulator. The helicopter simulator is then validated through a pilot in-the-loop experiment with five licensed helicopter pilots. Subjective as well as objective metrics are considered for the evaluation. Results suggest that the proposed flight simulator can be effectively used in flight schools to save flight hours for the training of novice pilots. However, for training expert pilots a more complex setup would be necessary, able to provide additional features like the motion cueing.

1. INTRODUCTION

Helicopter training is quite expensive, time consuming and often dangerous[11]. The use of simulators for civil and commercial training could minimize these factors, provided that a positive Transfer of Training (ToT) to an actual aircraft is guaranteed. However, simulators with high visual and motion fidelity are often expensive. Furthermore, the process to attain simulations that provide a positive ToT is very cumbersome[3]. For this reason, helicopter simulators are mostly established to train experienced pilots for special procedures, but are still not broadly used for training basic piloting skills. Having simpler and cheaper flight simulators could enable flight schools to adopt them as alternative to training in the actual helicopter.

The goal of the paper is to show the steps necessary to create a cost-effective helicopter simulator that can be used for basic piloting training. A key step is the development of a helicopter Flight Dynamics Model (FDM) that can replicate the unstable behavior and the most important couplings of the real aircraft. In fact, these are the main characteristics that expert pilots expect to perceive in a reliable simulator and that a novice pilot has to experience in order to learn a proper control task strategy.

Off-the-shelf helicopter simulation models often do not provide source code. This makes very difficult to re-implement such models, to modify certain characteristics or to integrate them with different simulators.

The implementation of a FDM can be done via identification or from first-principles. Identified models[5,12,9] can provide realistic flight characteristics but are specific of one unique rotorcraft and often valid only for one trim condition. On the other hand, physical based models can provide a description of the entire flight envelope but are very complex to design and require many parameters which are often not available in literature[4 6]. However, the model complexity could be reduced by excluding those equations and parameters that are not perceivable in simulations by a human pilot or not used to control a helicopter. Therefore, in this study a physical based FDM is build from first-principle using selected equations available in literature. During the model development, the tuning of the non-readily available parameters was performed based on the feedback provided by a licensed R22 pilot, while performing pilot-in-the-loop simulations. The goal was to ensure adequate response characteristics while maintaining minimal complexity of the FDM. In particular, attention was paid to include only those equations and parameters which could noticeably be perceived by the pilot.

To allow for piloted simulations, the FDM was then integrated in a simulator environment. To achieve cost-effectiveness, commercially available off-the-shelf helicopter controls and a Virtual Reality headset were integrated to create a cheap fixed-based simulator.

The implemented helicopter simulator was validated through a pilot in-the-loop experiment by asking five licensed helicopter pilots to accomplish different maneuvers.

The paper is organized as follows. In section 2 the implemented FDM is described. The integration into a fixed-based simulator is presented in section 3. The validation experiment is shown in section 4. Finally, discussions and main conclusions are provided.

2. FLIGHT DYNAMICS MODEL

A physical based model was built from first-principle. Equations available in literature were selected, to obtain a model that can be adapted to different helicopter characteristics by changing only few easily accessible physical parameters. In this work, parameter values of the Robinson R22 were used since this helicopter is often used for pilot training.

The FDM, shown in (Fig. 1) contains all necessary blocks to simulate the basic flight response characteristics of a helicopter. Descriptions for the main helicopter components *Main Rotor*, *Tail Rotor*, *Empennage* and *Fuselage* were integrated in the *Thrust Coefficients* and *Helicopter Dynamic* block. In the following, the resulting descriptions to replicate basic helicopter behavior for piloted simulation are outlined for each component.

2.1. Thrust Calculation

The thrust magnitude of main and tail rotor is calculated iteratively. Pilot in the loop simulations showed that simplified descriptions for rotor thrust, assuming a uniform and constant induced velocity, did not result in realistic behavior as translational lift effects were missed. An iterative calculation of inflow and thrust, assuming a uniform induced velocity, as described in the momentum theory[4], turned out to be a good trade-off between realistic response and a straightforward description. The main advantage of this description is that the rotor thrust can be calculated without knowing the disc tilt or the rotor flapping relative to the rotor-shaft. The main rotor thrust coefficient C_t and the uniform component of inflow λ are calculated as in (eq. 1)[4]. These two parameters are function of pilot inputs and the local wind velocities. The thrust coefficient for the tail rotor C_{TT} is also determined by (eq. 1) using the tail rotor parameters. All these parameters for both rotors are readily available or easy to calculate and tune.

$$
\begin{aligned}
C_t = \frac{a_0\sigma}{4}\Bigg[&\theta_0\left(\frac{1}{3}+\frac{\mu^2}{2}\right)+\frac{\mu}{2}\left(\theta_{1sw}+\frac{\beta_w}{2}\right) \\
&+\left(\frac{\mu_z-\lambda_0}{2}+\frac{1}{4}(1+\mu^2)\theta_t\right)\Bigg]
\end{aligned} \tag{1}
$$

C_t – thrust coefficient [–]
a_0 – lift curve slope [$1/rad$]
σ – blade solidity [–]
θ_0 – collective pitch angle [rad]
μ – advance ratio [–]
θ_{1sw} – longitudinal cyclic input [rad]
β_w – sideslip angle [rad]
μ_z – normalized vertical inflow velocity [–]
λ_0 – uniform component of inflow [–]
θ_t – blade linear twist [rad]

2.2. Main Rotor

The main rotor dynamics were described assuming that the rotor behaves like a disk, as shown in Fig. 2, 3. The state of the Tip Path Plane (TPP) is described by the coning angle β_0, the longitudinal flapping angle β_{1c} and the lateral flapping angle β_{1s}. These flapping states contribute to the longitudinal and lateral rotor hub forces X_h and Y_h that are calculated with the equations presented in Ref.[1]. Piloted simulations showed that an accurate description of

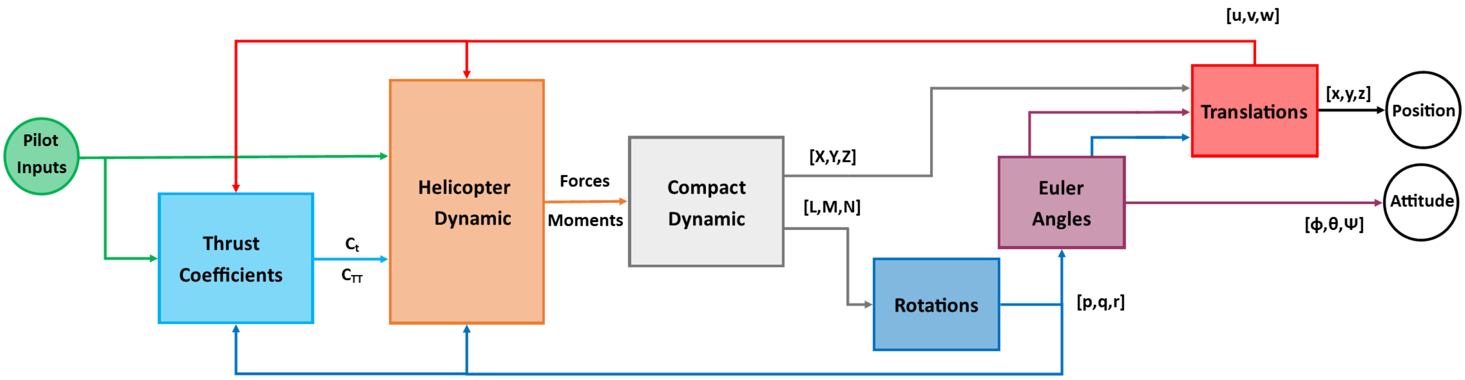

Figure 1: Helicopter-Model Structure

the β angles is crucial for a realistic helicopter behavior. A description, where the flapping angles are directly correlated to the pilot control inputs, as often considered in hover condition, did not result in controllable simulation behavior. Also common steady state response descriptions of the flapping angles did not provide major improvements. The dynamic helicopter responses were too unstable. Dynamic stability was increased significantly by using a second order differential blade-flapping equation (eq.2)[1] that finally felt realistic to fly for pilots. Finally, in the considered description the vertical hub force Z_h is determined by the thrust coefficient C_t.

$$\begin{bmatrix}\ddot{\beta}_0\\ \ddot{\beta}_{1c}\\ \ddot{\beta}_{1s}\end{bmatrix} + D\begin{bmatrix}\dot{\beta}_0\\ \dot{\beta}_{1c}\\ \dot{\beta}_{1s}\end{bmatrix} + K\begin{bmatrix}\beta_0\\ \beta_{1c}\\ \beta_{1s}\end{bmatrix} = F \tag{2}$$

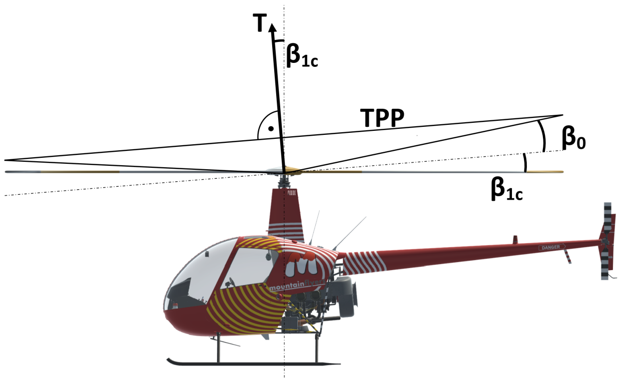

Figure 2: Longitudinal Flapping

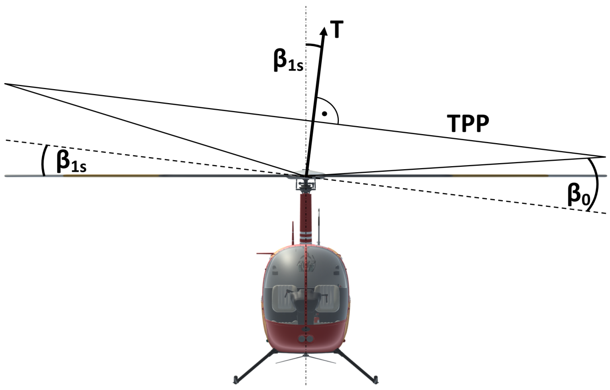

Figure 3: Lateral Flapping

2.3. Tail Rotor

The thrust force acting on the tail rotor hub is directly calculated by the thrust coefficient C_{TT}. Blade-flapping equations as well as main rotor downwash and empennage blockage effects[4,1] were not perceivable for pilots in simulation and were neglected. Because the dominant reaction of the tail rotor is the yawing moment N_{tr}, only N_{tr} was considered for the body force and moment calculation about the aircraft's Center of Gravity.

2.4. Empennage

In flight conditions different from hover, the empennage plays an important role. Horizontal tailplane and vertical fin stabilize the helicopter about its lateral and vertical axis and are crucial for simulation fidelity. In the developed model, these components are described with small wing sections using generic airfoil descriptions[1]. As can be seen in (eq.3), the velocity components are calculated in the local-body reference system. Therefore, the translational velocities $[u, v, w]$ and the angular rates $[p, q, r]$ of the helicopter are taken into account. $[l, b, h]$ are the distances from the Center of Gravity to the empennage. Equations 3-6 are shown for the tailplane. The same expressions were used to describe the fin.

$$\begin{bmatrix} u_{tp} \\ v_{tp} \\ w_{tp} \end{bmatrix} = \begin{bmatrix} u \\ v \\ w \end{bmatrix} + \begin{bmatrix} l_{tp} \\ b_{tp} \\ h_{tp} \end{bmatrix} \times \begin{bmatrix} p \\ q \\ r \end{bmatrix} \tag{3}$$

The total incidence velocity V_{tp} is given by (eq.4)

$$V_{tp} = \sqrt{u_{tp}^2 + v_{tp}^2 + w_{tp}^2} \tag{4}$$

Descriptions for main rotor downwash, contributing to local velocity components, did not lead to perceptible changes in piloted simulations. Therefore, the main rotor downwash was neglected to simplify the calculation, avoiding numerical singularities and the use of parameters that are generally hard to determine. The angle of attack α_{tp} and the sideslip angle β_{tp} vary with the local incidence velocities and are calculated by the equations (5, 6). α_{tp0} represents the airfoil's angle of incidence.

$$\alpha_{tp} = \tan^{-1}\left(\frac{w_{tp}}{u_{tp}}\right) + \alpha_{tp0} \tag{5}$$

$$\beta_{tp} = \sin^{-1}\left(\frac{v_{tp}}{V_{tp}}\right) \tag{6}$$

The airfoil's force coefficients, lift coefficient C_l and drag coefficient C_d, are calculated with generic descriptions for varying the angle of attack α and the sideslip angle β. Piloted simulations showed that more precise airfoil data increase the model complexity but do not change the perceivable flight characteristics.

2.5. Fuselage

Fuselage reactions contribute to simulation fidelity within varying translational and rotational movements. Forces and moments acting on the fuselage stabilize the helicopter response characteristics. Therefore, the fuselage is considered to provide three-dimensional drag forces X_f, Y_f, Z_f as well as a pitching moment M_f and a yawing moment N_f to represent the most important fuselage effects. The fuselage incidence angles, angle of attack α_f and sideslip angle β_f are used to calculate the force $[C_{xf}, C_{yf}, C_{zf}]$ and the moment $[C_{mf}, C_{nf}]$ coefficients to generate a profile which is common for many helicopters[4]. The aerodynamic forces and moments can then be calculated with just three fuselage parameters, plan area S_p, side area S_s and reference length l_f (eq. 7), which are easy to estimate for any helicopter.

$$\begin{aligned} X_f &= \frac{1}{2}\rho V_f^2 S_p C_{xf} \\ Y_f &= \frac{1}{2}\rho V_f^2 S_p C_{yf} \\ Z_f &= \frac{1}{2}\rho V_f^2 S_p C_{zf} \\ M_f &= \frac{1}{2}\rho V_f^2 S_p l_f C_{mf} \\ N_f &= \frac{1}{2}\rho V_f^2 S_p l_f C_{nf} \end{aligned} \tag{7}$$

2.6. Parameter Values

Parameter	Value	Unit	Meaning
Main Rotor			
m_{blade}	12	$[kg]$	Blade Mass
Empennage			
S_{fn}	0.21	$[m^2]$	Fin Area
S_{tp}	0.14	$[m^2]$	Tailplane Area
Fuselage			
S_p	2	$[m^2]$	Plan Area
S_s	3.5	$[m^2]$	Side Area
Inputs			
col_0	1.5	$[deg]$	Zero Collective
col_1	14.5	$[deg]$	Full Collective
δ_{long}	9	$[deg]$	Cyclic Range
δ_{lat}	9	$[deg]$	Cyclic Range
ped_l	19.5	$[deg]$	Left Pedal
ped_r	-10.5	$[deg]$	Right Pedal
Inertia			
I_{xx}	1305	$[kg \cdot m^2]$	Roll Inertia
I_{yy}	2980	$[kg \cdot m^2]$	Pitch Inertia
I_{zz}	2000	$[kg \cdot m^2]$	Yaw Inertia
I_{xz}	350	$[kg \cdot m^2]$	Product of Inertia

Table 1: Parameters

Table 1 shows the most important parameters that influence the response characteristics of the Flight Dynamics Model (FDM). Flight characteristics can be changed easily by tuning these parameters to increase model stability or to adapt to different simulation environments.

The blade mass m_{blade} affects the stability of the main rotor dynamics due to cyclic control inputs. A higher blade mass increases the blade flapping moment of Inertia I_β that leads to a higher static stability of the Tip Path Plane. Increased empennage areas S_{fn} and S_{tp} stabilize the pitching and yawing responses of the helicopter. Translational movements can be damped by increasing the fuselage areas S_p and S_s. Control sensitivity of the different axes can be adjusted with the input parameters that represent the blade pitch angles in degree of the main and tail rotor, respectively. As precise Inertia values were unknown for the R22, these values were selected to be between known values of a smaller ultra-light helicopter and those of the larger Bo105.

All parameters were tuned with pilot in the loop simulations during the model development. Reasonable physical values for the R22 were assumed as a starting point and adjusted to improve fidelity of the simulator.

3. SIMULATION ENVIRONMENT

To create a simulator accessible to general aviation flight schools, the model was integrated into a cheap off-the-shelf setup. Most professional full flight simulators use sophisticated motion platforms that provide motion cues to reproduce a realistic flight experience. Performing helicopter flight simulation is especially complicated, as it requires high gain motion cues with minimum delays. Even small helicopter movements should be replicated smoothly to provide useful sensory cues for pilots, especially for hover maneuvers. However, the movements of a helicopter to perform a sustained flight simulation can not be transfered to a motion simulator with a limited workspace. Simulator movements have to be reduced significantly to avoid reaching the workspace limits. Only advanced motion cueing algorithms could solve this issue by optimizing and reducing simulator movements. Due to this reasons, the design of a low cost motion simulator for helicopter flight simulation is quite challenging. Expert helicopter pilots generally rely on motion cues and the task performance increases significantly with perceived motion, as shown in previous experiments[10]. But recent results seem to suggest that motion in simulators shows only minor benefits in training of novice pilots compared to fixed-base simulators[3]. This means that a fixed-base set-up does not necessarily minimize the training effectiveness. On the other hand, the visual environment and realistic helicopter controls turned out to be essential for an effective training simulator[2].

Therefore, the Pro Flight Trainer Puma controls[14] and the HTC VIVE VR headset system[7] were considered to implement a cheap fixed-base simulator, Fig 4. Aerofly FS2[8] is used as visualization software and includes a detailed graphics model of the R22, as shown in Fig. 5. This set-up is a good trade-off between costs and the possibility to have a realistic flight simulation environment. A big advantage is the use of just one desktop computer in combination with portable helicopter controls and a compact visualization system that provides a wide range of view.

Figure 4: Simulator Set-up for the experiment

4. PILOT VALIDATION

To show that the simulator set-up provides a proper flight environment for pilot training, eight participants were asked to test the helicopter simulator.

Three participants, who had helicopter experience from simulators as well as from real helicopters, were able to complete a pre-experiment and to provide feedback on the chosen model pa-

Figure 5: Cockpit View

rameters listed in table 1. These parameters were tuned with only one R22 pilot during the model development. Because this pilot might have adapted to the model behavior, it was necessary to evaluate with different pilots the adjusted parametric values. Therefore, different parameter values were tested in a random order. All three participants of this pre-experiment independently rated the same parameter values as the most adequate and most realistic for this simulator set-up. These values were used for the further final validation experiment. During the pre-experiment, some pilots complained about the control devices. In particular, the collective lever and the pedals were described as "too loose". Therefore, some minor changes were done to increase the friction in the controls before the final experiment.

For the final validation experiment, five other licensed R22 pilots, who were not familiar with this simulator set-up, were asked to accomplish specific maneuvers.

4.1. Experiment Design

Five licensed R22 pilots accomplished the final validation experiment. The experiment started with a familiarization phase to get used to the simulator environment. This phase was limited to 15 minutes, to avoid a possible adaption to the setup or to the simulated environment, which could have prevented the pilots to properly assess the model and the simulator. At the beginning, a standard desktop monitor was used to avoid motion sickness induced with the use of the VR headset in case of instability. When the pilots were able to stabilize the model, the VR headset was used. After the familiarization phase, the pilots were asked to accomplish the following maneuvers:

1. *Precision Hover*
   Stabilize the helicopter over a marked position and hold position for 30 seconds
2. *Lateral Reposition*
   Stabilize the helicopter in front of a taxiway centerline, move sidewards to the next taxiway, hold short and move back sidewards to the initial position
3. *Hovering Turns*
   Perform full turns with the pedals in both directions while holding position
4. *Acceleration-Deceleration*
   Line up on the runway, accelerate to moderate forward speed and decelerate to a full stop

Each participant repeated each maneuver three times.

4.2. Results

A first result was that three pilots had difficulties to adapt to the simulation environment within the familiarization phase. An explanation for this result is given in the discussion. Because they could not stabilize the helicopter in such a way that they could perform specific maneuvers, it was decided to exclude these pilots from the final experiment.

The other two pilots could complete all the experiment regularly. These pilots were asked to give a subjective fidelity rating from 1 to 10 according to the Simulator Fidelity Rating scale[13]. Table 3 shows an extract of this rating scale explaining the levels of comparative task performance and pilot's task strategy. The ratings are used to evaluate the level of adaptation necessary to fly the simulator. Therefore, it is a measure of the realism of the simulator.

The pilots were asked to give two different ratings. The first rating was for the Flight Dynamics Model itself (Tab. 2). For this rating the pilots were asked not to take into consideration all perceived disadvantages of the simulator set-up, e.g. the lack of motion. The pilots could not detect wrong behavior of the Flight Dynamics Model (FDM) and had the overall impression that the FDM requires moderate adaption of task strategy and allows equivalent task performance. The second rating was for the whole simulator set-up to evaluate how useful this simulator training could be for novice pilots. Both pilots had the impression that they could fly the maneuvers more precisely in the real helicopter although they achieved a comparable performance.

This can also be seen in the recorded flight data of the experiment that were used for objective task performance evaluation. As an example, Fig. 6 and

Maneuver	Pilot A	Pilot B
Precision Hover	5	5
Lateral Reposition	5	4
Hovering Turns	4	4
Acceleration-Deceleration	4	3

Table 2: Ratings for the Flight Dynamics Model

7 show the ground speed during the third trial of the hover maneuver for both pilots (A and B). Variances in Heading during the Hover Maneuver can be seen in Fig. 8 and 9. Although both pilots could perform a stable hover maneuver, the task performance was slightly worse compared to the real helicopter. This tendency could also be seen in the objective evaluation of all other maneuvers. However, all maneuvers could be flown in a coordinated way. Worse task performance was expected for expert pilots that are not familiar with this simulator set-up. Besides the adaption to the artificial controls and the visual environment, the absence of motion in the fixed-base set-up seems to be the main reason for this result. Further experiments with a motion platform could prove this assumption and may also lead to better subjective ratings.

Both pilots said that the simulator could be very beneficial for novice pilots and that they would have used it themselves for initial training.

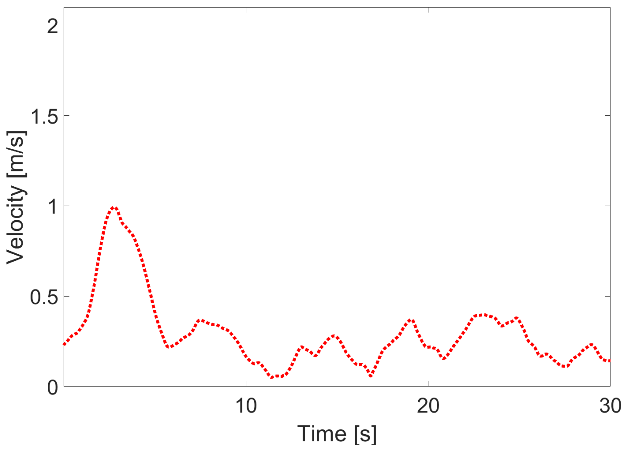

Figure 6: Ground Speed Hover Maneuver (Pilot A)

5. DISCUSSION

Results highlighted that expert pilots are sceptical about such a simple simulator set-up and have to adapt their control task strategy with respect to when they fly in a real helicopter. Because of this, the majority of experienced pilots has difficulties at

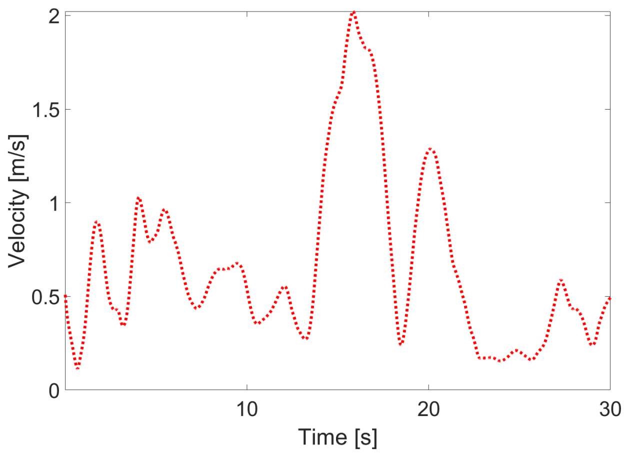

Figure 7: Ground Speed Hover Maneuver (Pilot B)

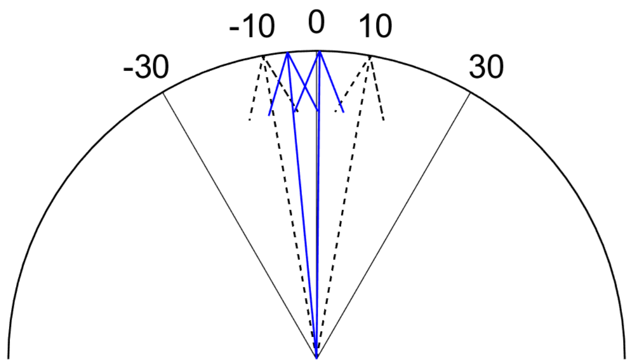

Figure 8: Heading Variation in deg. for Hover Maneuver (Pilot A)

evaluating the effectiveness of a training in such a simulator and to compare this training with the one generally performed on a real aircraft. This comparison becomes even harder if a pilot adapts to the simulator and is not able anymore to make a proper comparison with respect to the real flying experience.

The five pilots considered for the final experiment were divided into two groups. Three pilots (group 1) had neither experience with computer games, nor with flight simulation software before. This group of pilots had difficulties to adapt to the simulation environment in the short time period of the experiment. Generally, they complained about the lack of adequate motion and visual cues and therefore could not stabilize the helicopter in simulation. Furthermore, these pilots could not use the advantages of the Virtual Reality (VR) headset as they felt immediately uncomfortable due to motion sickness. Indeed, motion sickness can easily arise if using VR headsets in an unstable condition, which generates

Comparative Task Performance	Pilot's Task Strategy	Fidelity Rating
Equivalent performance attainable	Negligible or no adaption	1
Equivalent performance attainable	Minimal adaption	2
Similar performance attainable	Minimal adaption	3
Equivalent performance attainable	Moderate adaption	4
Similar performance attainable	Moderate adaption	5
Similar or Equivalent performance attainable	Considerable adaption	6
Similar or Equivalent performance attainable	Excessive adaption	7
Similar performance not attainable	Considerable or less adaption	8
Similar performance not attainable	Excessive adaption	9
Similar performance not attainable	An entirely inappropriate task strategy is required	10

Table 3: Simulatior Fidelity Rating Scale[13]

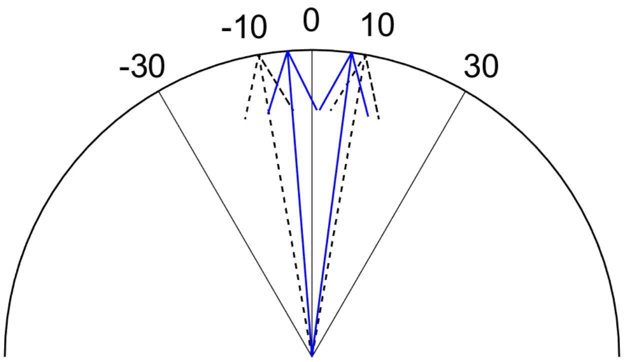

Figure 9: Heading Variation in deg. for Hover Maneuver (Pilot B)

a fast moving visual scenery. Providing additional motion cues could help to avoid this issue. Overall, group 1 had the impression that the entire simulator set-up would require excessive adaptation of task strategy compared to the real helicopter. However, this group seems to have a general problem with the adaptation to simulation environments and it is not a specific issue of this simulator set-up. These pilots would just need more simulation experience to accept different characteristics compared to the real aircraft.

In contrast, the two other pilots of group 2 were able to stabilize the helicopter after few trials. Both had experience with computer games and home use flight simulation software. This experience enabled them to adapt to the simulator within a short time and to fly all conceivable maneuvers. With the use of the desktop monitor, the pilots of group 2 also complained about adequate visual cues and could not detect helicopter movements precisely to counteract disturbances. This was no longer an issue with the VR headset, as the pilots really enjoyed the advantages of the wide range of view including head movements.

It was behind the scope and financial framework of this work to prove that a positive Transfer of Training (ToT) can be provided to a real helicopter for pilots. However, results of previous experiments[2] seem to suggest that also the simulator set-up presented here is adequate for the training of novice pilots. Expert pilots, who tested this previous set-up, missed some characteristics and expressed doubts regarding a positive ToT. However, expert pilots with experience in actual helicopters only, are generally very critical when they evaluate simulators as they expect a precise copy of the real aircraft. This was also the impression obtained from the experiment conducted in this study. Therefore, the training effectiveness in simulators could be greater than predicted, at least for novice pilots.

6. CONCLUSIONS

Helicopter flight simulators could gain great importance in the training of pilots improving safety and effectiveness of the training process in the future. However, today adequate helicopter simulation environments are not accessible for general aviation flight schools. The main goal of this paper was to define which characteristics are necessary to develop a cheap helicopter flight simulator for training.

To achieve this goal, an open-source helicopter Flight Dynamics Model with minimal complexity was implemented, integrated in a low cost flight simulator set-up and validated through pilot-in-the-loop experiments. Based on the experiment results, it seems that once a pilot can adapt to a simulation environment and accepts different characteristics, e.g. the lack of proper visual and motion cues compared to reality, it is not a hard task to stabilize this helicopter simulator and to fly all conceivable maneuvers. Furthermore, pilots that were able to fly this helicopter simulator were not missing basic response characteristics and considered the Flight Dynamics Model as quite realistic.

From the result of the experiment, it can be concluded that the whole set-up could be very helpful for novice pilots to train basic flying skills. However, for training expert pilots some improvements of the setup are necessary. Indeed, features like motion cueing are generally very appreciated by experienced helicopter pilots. Therefore, a motion simulator seems to be necessary to create an accurate and reliable helicopter training simulator.

REFERENCES

[1] Beibei Ren, Shuzhi Sam Ge, Chang Chen, Cheng-Heng Fua and Tong Heng Lee. *Modeling, Control and Coordination of Helicopter Systems*. Springer, 2007.

[2] Fabbroni D., Bufalo F., D'Intino G., Geluardi S., Gerboni C., Olivari M., Bülthoff H.H. Transfer-of-training: From fixed- and motion-base simulators to a light-weight helicopter. *American Helicopter Society*, 2018.

[3] Fabbroni D., Geluardi S., Gerboni C., Olivari M., Pollini L., Bülthoff H.H. Quasi-transfer of helicopter training from fixed- to motion-base simulator. *European Rotorcraft Forum*, 2017.

[4] Gareth D. Padfield. *Helicopter Flight Dynamics: The Theory and Application of Flying Qualities and Simulation Modelling, Second Edition*. Blackwell Publishing, 2007.

[5] Geluardi S., Nieuwenhuizen F.M., Venrooij J., Pollini L., Bülthoff H.H. *Frequency Domain System Identification of a Robinson R44 in Hover*. AHS International, 2018.

[6] Gerboni C., Geluardi S., Olivari M., Nieuwenhuizen F.M., Bülthoff H.H., Pollini L. Development of a 6 dof nonlinear helicopter model for the mpi cyber motion simulator. *European Rotorcraft Forum*, 2014.

[7] HTC. VIVE ®. `https://www.vive.com/de/`.

[8] IPACS. Aerofly FS2 ®. `http://www.aerofly.com/aerofly_fs_2_overview_de.html`.

[9] Jay W. Fletcher. *A Model Structure for Identification of Linear Models of the UH-60 Helicopter in Hover and Forward Flight*. NASA Technical Memorandum, 1995.

[10] Jeffery Allyn Schroeder. Helicopter flight simulation motion platform requirements. *National Aeronautics and Space Administration*, 1999.

[11] Lee Roskop. U.s. rotorcraft accident data and statistics. *FAA/Industry Safety Forum*, 2012.

[12] Mark B. Tischler, Robert K. Remple. *Aircraft and Rotorcraft System Identification, Second Edition*. American Institute of Aeronautics and Astronautics, 2012.

[13] Philip Perfect, Emma Timson, Mark D. White, Gareth D. Padfield, Robert Erdos, Arthur W. Gubbels, Andrew C. Berryman,. A rating scale for subjective assessment of simulator fidelity. *European Rotorcraft Forum*, 2011.

[14] Pro Flight Trainer. Pro Flight Trainer Puma ®. `https://pro-flight-trainer-com.myshopify.com/`.