MODEL OF HELICOPTER PILOT'S CONTROLS ACTIVITY FOR SHIPBOARD OPERATIONS

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Abstract

The only approved means available to evaluate the dynamic behavior of the helicopter/pilot combination in the complex turbulent environment of the moving flight deck of a ship is the execution of actual at-sea flight tests. The development of an off-line simulation tool of helicopter shipboard operations for engineering and design purpose is desirable. The objective of this study is to identify the pilot's controls strategy in order to provide prediction of the controls' positions when flying typical on-shore representative shipboard maneuvers, namely, hover, "fore/aft" and "estern" approaches, into four different wind environment conditions. Operational pilots A, B, C and D performed a pilot-in-the-loop flight test simulation in the helicopter engineering flight simulator facility of ONERA Salon de Provence Center, so called *PycsHel*, in order to provide data to calibrate and validate the prediction of the basic SYCOS (*SYnthesis through COnstrained Simulation*) pilot model. The optimization process for training the pilot model from the piloted simulations data is divided into hover task and approach tasks, and uses the DIMSS PM (*Dynamic Interface Modeling and Simulation System Product Metric*) as metrics for estimating the pilot's controls activity. Pilots A and B models are considered valid for the validation data set in hover. However, basic SYCOS model is not able to keep the predictions stable over 50 sec of flight of the approach tasks. Therefore, extensions to the basic SYCOS model are studied by implementing an attitude or an acceleration feedback parallel line, in order to provide stability strategy to the pilot's controls activity prediction. The attitude feedback strategy is the only able to restore the SYCOS model stability for the approach data set. The extended SYCOS model with attitude feedback strategy is used for training and allows the validation of pilot's activity model to approach type "estern" (pilot B). None pilot's controls activity model is valid for the "fore/aft" approach task. The pilots C ("estern" approach) and D ("fore/aft" approach) extended SYCOS models are able to provide satisfactory predictions only for collective and pedals activities.

Nomenclature

K	Crossover gain vector
$K\dot{u},\dot{v},\dot{w},\ddot{\psi}$	Acceleration feedback gains.
$K\phi$, $K\theta$	Attitude feedback gains.
Ddc, Ddl, *Ddm, Ddn*	Collective, lateral cyclic, longitudinal cyclic and pedal positions.
p, q, r	Angular velocity components about fuselage *x*-, *y*- and *z*- axes.
u, v, w	Ground velocity components about fuselage *x*-, *y*- and *z*- axes.
u_e, v_e, w_e	Ground velocity components about Earth referenced axes.
Φ, θ, ψ	Euler angles defining the orientation of the aircraft relative to the Earth.
Φ_{Ref}, θ_{Ref}	Referenced roll and pitch angles.
$\dot{u},\dot{v},\dot{w},\dot{\psi}$	*u*, *v*, *w* and ψ differentiation with respect to time.
ζ	Time delay.
$\ddot{\psi}$	Yaw angle second differentiation with respect to time.

1. INTRODUCTION

Helicopter shipboard launch and recovery operations continue to be a topic of interest for both civil and military operators, which request the maximum of helicopter/ship (or platform) operational capability that can be exercised in any environmental condition [1].

To evaluate the dynamic behavior of the helicopter/pilot combination in the complex turbulent environment of the moving flight deck of a ship the execution of actual at-sea flight tests, sometimes referred to as *Dynamic Interface* (DI) testing, is the only approved means available at present [2].

Since the flight-testing is to be carried out on board a ship in a limited period of time, the exact conditions at which tests can take place cannot be determined beforehand. This often leads to overly conservative envelope of flight that are limited by scheduling and meteorological constraints, rather than by aircraft or pilot limits [3].

Important improvements have been performed in the field of helicopter flight dynamics modeling over the last two decades. Actually, recent models demonstrate good capabilities in capturing the major flight conditions including flights cases close to the limit or operational flight envelopes. The *Computational Fluid Dynamics* (CFD) coupled (or similar complex aerodynamic models coupling) to flight dynamics tools has enabled the physical modeling of critical flight situations where aerodynamics becomes complex. As consequence, over the last few years, numerous efforts around the world have been devoted to develop helicopter/ship dynamic interface simulation tools.

In this context, ONERA, *The French Aerospace Lab*, has been researching models to support maritime operation of helicopters since later 90s. Several of these models and simulations tools have been installed in the engineering flight simulator facility, so called *PycsHel – Prototype and Design of Helicopter Systems,* of the Department of Systems Controls and Flight Dynamics, DCSD, of ONERA Salon de Provence center.

As a support to at-sea flight tests preparation and completion the development of an off-line simulation tool of helicopter shipboard operations for engineering and design purposes would be desirable. For instance, such a simulation tool could be used to:

-find optimal approach and departure paths;

-improve safety and efficiency of the helicopter/ship qualification flight testing.

-identify a preliminary perimeter of SHOLs in preparation of at-sea flight tests

-optimize helicopters and ships designs to naval operations missions;

-assess the impact of design changes to both helicopter and ship; and

For this, the development of a dynamic control element that can replace the pilot-in-the loop simulations is needed for performing typical shipboard helicopter tasks, with representative control's strategy of human pilots.

Over the last several decades, the extensive effort in developing feedback control theory has also proven to be quite useful in quantifying control-related human behavior [4].

Early research on the human pilot model was devoted to understanding the characteristics of the human as a controller of single input, single output linear time-invariant systems.

MCRUER and JEX [5] used a set of quasi-linear models that are adept at predicting human behavior. The quasi-linear model, so-called crossover model, is very useful for analyzing closed-loop compensatory tracking or state regulation tasks in which human operator attempts to minimize some displayed system error [4].

TURNER *et al.* [6] have developed a general pilot model, called SYCOS (*SYnthesis through COnstrained Simulation*), which includes the linear time-invariant inverse model and crossover model, to simulate deck landing tasks as performed for establishing limits for helicopter-ship operations.

Comparison with flight test data from piloted simulation confirmed the capacity of SYCOS model to satisfactory simulate pilot's guidance and response to environment disturbances in ship deck operations.

BRADLEY and BRINDLEY [7] have continued the development of the SYCOS model by applying it on several different rotorcraft types and tasks from ADS-33 [8] and some operational ones to be performed, in order to enhance the realism of the control activity.

They confirmed the affectivity of SYCOS model at piloting rotorcraft through prescribed flight paths into an atmospheric turbulent environment by replicating some features of the human pilot control activity.

VAN HOYDONCK and PAVEL [9] have developed a helicopter model in support of helicopter maritime landing operations and have used the SYCOS pilot model to execute fore/aft procedures and assess the aircraft handling qualities for ship deck operations.

Based on previous results of the use of SYCOS model on the prediction of pilot's controls activity of Dynamic Interface procedures, its intrinsic low computational charge (when compared to classical controls strategies) and, consequently, possibility to implement on offline and real-time simulation applications, the SYCOS model was selected to be studied, in this work, as a human pilot model.

This paper presents the methodology applied to characterize the human pilot's controls activity, based on the basic SYCOS model, when flying typical on-shore representative shipboard maneuvers.

In addition, this paper presents some studies of extensions in the basic SYCOS model, in order to provide stability strategy to it.

2. HELICOPTER ENGINEERING FLIGHT SIMULATOR FACILITY

The rotorcraft engineering simulator facility, so-called *PycsHel,* of the Department of Systems Controls and Flight Dynamics, DCSD, is installed at ONERA Salon de Provence Center. It is a test bench facility dedicated to assist helicopter systems and human factors researches.

This bench is a fully open and modular environment that allows to design, to implement and to test, in a real-time environment, the algorithms, models and systems blocks developed by ONERA. It is compatible with the implementation of models in any language (*Fortran, C, C++, Matlab*, etc) for the development of fully customizable scenarios.

The *PycsHel* test bench facility consists of:

-three-channel collimated visual projectors able to provide a horizontal field of view of 265° and a vertical field of view of 65°;

-2 side-by-side arranged seats in the internal configuration of a typical helicopter cockpit (left seat:

classical rotary wing controls sticks - cyclic, collective and pedals; and right seat: active side sticks for cyclic and collective controllers, offering a programmable haptic feedback, and a classic helicopter pedal control);

- reconfigurable computer-generated front panel composed of 3 tactile displays and a central console composed of one tactile display;
- graphic generator based on *OpenSceneGraph*, able to accommodate realistic visual databases;
- state-of-the-art non-linear realistic aircraft flight models (helicopters and UAV) and environment models (namely: turbulence, ship airwake, and sea); and
- control, data record and time history capture facility room.

A fourth collimated channel projector will be installed soon, in order to project the top view image of the scenario and improve the simulation realism.

In addition, *PycsHel* features a biophysical data acquisition hardware composed of:

- infrared tracking sensors;
- electromyogram sensors; and
- variable transparency helmet with head-tracking feature.

Figure 1 presents the cockpit interface of *PycsHel*.

Figure 1 – Cockpit view of *PycsHel* simulation facility.

3. PILOT-IN-THE LOOP FLIGHT TEST TRIALS

Late 2014, four operational pilots from Brazilian Armed Forces performed a pilot-in-the-loop flight test simulation in *PycsHel* facility, in order to provide data to calibrate and validate the prediction of pilot's control activity model.

All pilots have different background concerning the type of aircraft and operational mission already accomplished. The Table 1 presents a summary of their operational experience.

Table 1- Summary of operational background of the pilots.

Experience	Pilot			
	A	B	C	D
Total of flight hours	4,150	1,770	2,250	1,850
Class of rotorcraft flown	Heavy, medium and light	Heavy and light	Heavy, medium and light	Heavy, medium and light
Deck landing	None	180	None	130

The tests were performed in a realist heavy helicopter nonlinear aeromechanics model, with a simplified SAS (*Stability Augmentation System*) incorporated.

The flight conditions are maximum allowed weight and maximum aft CG at sea-level ISA+15.

It was established three land-based tasks representative of shipboard operations.

The selection of the tasks maneuvers as well as their levels of desired and adequate performances were established and/or adapted based on:

- typical shipboard operating profiles used by some Navies around the world;
- launch and recovery procedures described in AGARD [2];
- missions tasks defined in ADS-33 [8];
- results of MITCHELL *et al.* [10] that proved the validity of the use of landing-based Hover task, as defined in the ADS-33, to evaluate handling qualities when ship motions are low, as big ships; and
- *PycsHel's* models and images resources availability (model of touchdown and 4th projector image were not available at the time of the flight simulation trials).

Table 2 presents a detailed description of these tasks and respective required levels of performance. Figure 2 presents the general course scheme. The pilots did not assign any handling qualities rating and the performance levels were used as an index of task accomplished.

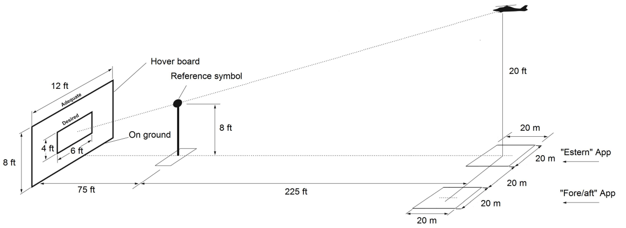

Figure 2 - Test courses environment schematic view.

In order to allow different levels of pilot's controls activity and workload to perform the same task, each task was flown in four different environments: no wind; 15 kt constant left crosswind; 20 kt constant head wind; and 20 kt constant head wind in a 3-axis turbulent environment (wind standard deviation around ±2,5 m/s in each fuselage axes). This turbulence values is representative of some difficult conditions presented in maritime operations.

All pilots run the hover task and the group was subdivided into two groups, of 2 pilots each, to perform "fore/aft" (pilots A and D) and "Estern" approach tasks (pilots B and C).

Before the test flight trial, each pilot conducted an adaptation flight to the simulator handling qualities and its main features.

Figure 3 presents some images of these flight tests.

4. SYCOS MODEL

The SYCOS pilot model came into being, in 1996, as a dynamic controller for helicopter simulations, which could pilot a helicopter through prescribed maneuvers in a manner similar to a human pilot [11].

The basic SYCOS model consists of the pilot vehicle quasi-linear model of MCRUER and JEX, added a linear time-invariant approximate inverse model. That is, in case of a perfect system inversion, the SYCOS model is reduced to MCRUER and JEX crossover tracking model.

Figure 4 presents the basic SYCOS model structure.

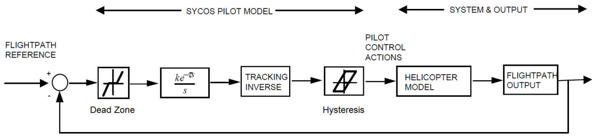

Figure 4. SYCOS schematic structure with nonlinear elements (Ref [6]).

In physical terms, in the crossover model, the pilot adjusts his behavior to compensate for the perceived visual dynamics of the system being controlled (error between prescribed and actual flight-path), while the inverse model represents the pilot's adaptation to the helicopter dynamics (it acts as the "learned response" of the pilot, his internalized model of vehicle behavior).

Comparisons of controls records from human pilots with those from SYCOS model performed by TURNER *et al.* [6], demonstrated the importance of incorporating, at least, two nonlinear elements to improve the controls displacement prediction and, consequently, enhance the realism of the control activity. Namely:

-"Dead Zone": represents a threshold of pilot's perception of departure from the reference values (generates zero output within a specified region); and

-"Hysteresis": represents a system in which a change in input causes an equal change in output. However, when the input changes direction, an initial change in input has no effect on the output. Physically, it replicates the stepped nature of the pilot activity on the controls.

The principal difference between the SYCOS model and inverse simulation lies in its configuration as a corrective system. That is, instead of the open loop structure where a set of control actions are generated from a reference output value, they are calculated from the difference between the reference output values and the outputs' current actual values [7]. The pilot model generates a vector of controls that follows the reference, reflecting the fact that the controls act directly to produce accelerations.

It adapts to the characteristics of the helicopter type being flown and it is designed to produce corrective control actions in response to external stimulus (as atmospheric turbulence). Therefore, it permits to emulate pilot control activity during maneuvering flight, even in a turbulent environment, in a more realistic manner than the "perfect pilot" of inverse simulation.

The mathematical development of the basic SYCOS model and its flightpath vector options are detailed in References [6], [11] and [12].

For this work, it was selected the following flightpath vector, *y*:

(1) $$y = [u\ v\ w\ \dot{\psi}]$$

This choice is justified by the fact that the helicopter controls are directly related to the movement on its body reference axes and the lower number of parameters to be adjusted in the basic SYCOS model.

5. CONTROLS' ACTIVITY METRIC

In this work, the DIMSS PM (*Dynamic Interface Modeling and Simulation System Product Metric*) is the selected metric for estimating the pilot's controls activity.

The DIMSS PM was first developed by ROSCOE and WILKINSON [14] for evaluation of helicopter ship deck landings. Several studies have shown correlations to subjective workload ratings and handling qualities ratings during tests where turbulence is the driving factor for workload [13].

The DIMSS PM is the product of the number of control reversals and the standard deviation of control deflections in a moving 3 sec window [13].

A control reversal is defined as a local maximum or minimum in the control inceptor (pedals, lateral cyclic, longitudinal cyclic and collective) deflection time history.

The premise of this metric is that high frequency (large number of control reversals), large amplitude control movements, resulting in high values of the metric, represented high pilot workload (pilot's activity). Similarly, low frequency, low amplitude control movements, resulting in low values of the metric, represented low pilot workload.

Since the pilot's activity is not confined to one control axis during the execution of the task, the combination of the activity from all control axes is determined by the sum of the mean DIMSS PM for each control (more details presented at [14]).

6. EXTENSIONS IN SYCOS MODEL

According to TURNER *et al*. [6], the SYCOS model is able to guide the helicopter along the piloted flight path (to follow the exact trajectory flown by the pilots). However, it was not guaranteed that it would also keep the helicopter completely stable around this flight path. As the SYCOS does not augment stability of the system [6], the free modes were still present in the overall system.

In addition, BRADLEY and BRINDLEY [12] verified that the inverse component of the SYCOS model introduces a zero dynamics feature on the systems, which could engage oscillations in both lateral and longitudinal axes of the predicted control actions (following external disturbances).

In the present work, the aircraft model features an unstable long-term mode in hovering flight (about 17 sec of period).

For the hover task, in which was required a 15 sec of stabilized flight, the basic SYCOS model is able to perform the maneuver without any instability.

For the approach tasks, the basic SYCOS pilot model is able to guide the helicopter along the piloted flight path (to follow the exact trajectory flown by the pilots), only for around 50 sec of flight. Over this time, the basic SYCOS model does not keep the aircraft stable around its required flight path (an initial *u* and *v* divergent oscillation followed by a fully divergent prediction). Nevertheless, all approach tasks are performed in a period greater than 90 sec of flight simulation.

Figure 5 presents an example of the prediction divergence of the state vector for a basic SYCOS structure.

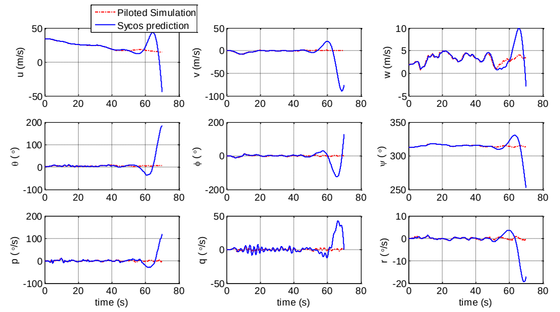

Figure 5. Example of divergence of the basic SYCOS prediction for training data set.

Even for the hover task, independent of the SYCOS' parameters selection, the prediction diverges following over 30 sec of flight simulation. That is possible to be observed because some of the pilots maintained up to 40 sec of stabilized hover degrading his performance levels, for training purposes only.

These features allow the use of basic SYCOS model to identify the pilot's controls activity model for the hover task, being less than 30 sec. However, it precludes the use of SYSCOS for the case of the approach tasks. This illustrates that the pilot has a wider task than following path references for a long term and that the basic SYCOS model has limitations in some aspects.

Consequently, in this work, it is studied extensions to the basic SYCOS model. The proposal is to implement a stability feedback parallel line, in order to provide stability strategy to the pilot's controls activity prediction, specially, in the low airspeed regime.

The following hypotheses are tested:

-Attitude feedback: the pilot knows the initial trimmed pitch and roll attitude angles and use them as reference; or

-Acceleration feedback: the pilot feels the actual aircraft's accelerations and uses them to control the aircraft.

Figures 6 and 7 present the general architecture of the suggested extensions of SYCOS model.

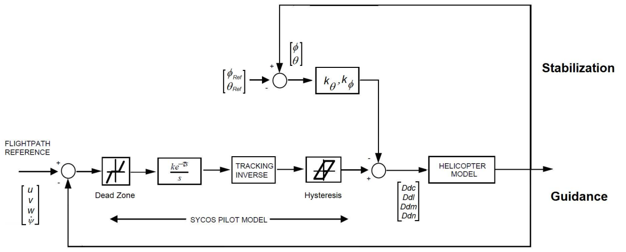

Figure 6. General architecture of extended SYCOS model with attitude feedback (adapted from Ref [6]).

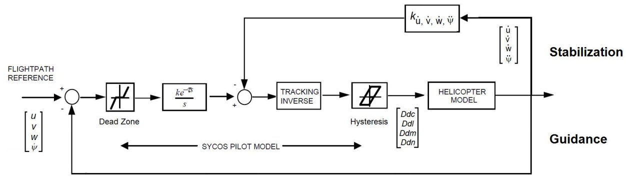

Figure 7. General architecture of extended SYCOS model with acceleration feedback (adapted from Ref [6]).

In this way, the extended SYCOS model consists of the basic SYCOS model as "Guidance" feedback line, in which the objective is to estimate the pilot's controls activity for tracking the flight path reference, increased by a so-called "Stabilization" line, which is able to predict the pilot's controls actions for stabilizing the rotorcraft along this flight path.

7. PILOT'S CONTROLS ACTIVITY RESULTS

For each pilot, the pilot's control activity model is divided into two types of maneuvers: hover and approach.

In addition, each maneuver is subdivided into two more sets: training (20kt head wind with atmospheric turbulence) and validation (no wind, 20 kt head wind and 15 kt left crosswind).

The training set is selected based on its high level of pilots' activity on all helicopters controls, among the existing data, allowing correlate it with a more general piloting strategy.

7.1. Training

The optimization process for training the pilot model from the piloted simulations data is divided into hover task and approach tasks case.

This procedure is due to instabilities presented in the predictions of the approach tasks, which are not observed in the hover task, for the recorded test data. It is not necessary to implement the proposed stabilization line for the execution of 15 sec of stabilized hover. Then, the activity of each pilot is modeled by the basic SYCOS.

Two types of helicopter models are verified: linear and "semi-linear". The so called "semi-linear" is a linear model interpolated by the forward speed flight, with nonlinear inertial couplings and gravity effects for ϕ and θ.

All pilots only achieved the adequate performance level for the overall tasks of the training data set.

7.1.1. Hover task

7.1.1.1. Process

The process to calibrate the basic SYCOS pilot model from the hover piloted simulations data is based on sensibility analysis of the control's activity prediction.

At every stage of this process, the aim is to find a good fit level of the temporal variation of the pilot's controls (collective, pedals, lateral and longitudinal cyclic movement), within a satisfactory flight path tracking error.

Firstly, maintaining up fixed the crossover gain values, it promotes the analysis and selection of the following parameters on the prediction of the pilot's controls activity:

a) inverse matrix model; and

b) helicopter model (linear or semi-linear).

Secondly, once selected the inverse matrix and the helicopter models, the crossover gains are preliminarily adjusted, by trial and error, keeping null all other parameters of the basic SYCOS model.

Next, an optimization code is used for refine the crossover gains adjustment, using *Matlab*® existing resources for nonlinear models (*lsqnonlin* command), in order to obtain an optimal curve fit (minimal controls prediction error at each time step) by the least squares method.

For this, it is defined a sequence of crossover gains to be changed separately based on the influence of each type of gain in the control of the aircraft, as well as the couplings between them.

For the specific helicopter model of the present work, the following optimization sequence is defined, from larger to lower axes couplings:

a) minimize longitudinal and lateral cyclic prediction errors by optimizing crossover gains in u and v axes;

b) minimize collective prediction error by optimizing the crossover gain in w axis; and

c) minimize pedal prediction error by optimizing crossover gain in $\dot{\psi}$.

Once optimized one crossover gain, this is considered fixed for the next stage of optimization.

Except for the optimization process of u and v errors, in which is used a cost function of the sum of the normalized prediction errors, the others use a simple cost function of the control's prediction error.

Finally, the optimized crossover gains are used as a reference for fine adjustment of the pilot model, by trial and error, with all other parameters of the SYCOS model (namely:, time delay, dead-zone and hysteresis values).

In this final step of the optimization process, the definition of the pilot's activity model is not only based on the prediction curve fit of the controls and the flight path, but also in the capacity of providing useful pilot's activity information.

For that, based on the previous studies presented in section 5 of this paper, it is used the sum of the mean DIMSS PN in each control axis as pilot's activity reference metric.

Thus, the pilot model resultant of the training process is the one that reduces the prediction errors of controls and flight path with an approximated level of control's activity displayed by the human pilot while performing the task.

7.1.1.2. Results

Table 3 presents the identified basic SYCOS model for predicting pilot's control activity of hovering task. For all pilots, the performance level attained is adequate and the selected inverse matrix model is at 0 kt flight condition, as expected.

Table 4 presents a comparative between the DIMSS PM values of the pilot-in-the-loop flight data and its respective identified basic SYCOS model.

Figures 8 and 9 present an example of results of the identified pilot's activity model for the hovering training data set of pilot A.

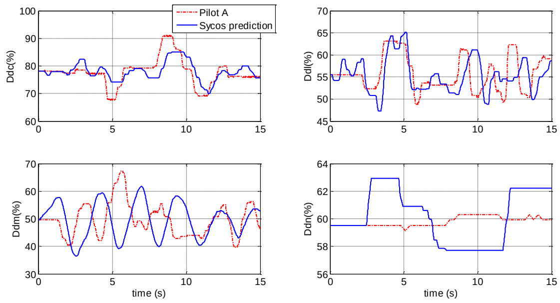

Figure 8. Prediction of pilot's control activity of hovering training data set.

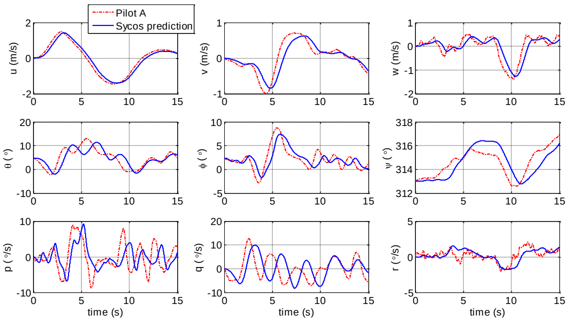

Figure 9. Prediction of state variables of hovering training data set.

In general, for all pilots of this work, it is possible to maintain a satisfactory level of flight path tracking, as presented in Figure 9. Additionally, it is reached a good prediction level of collective's activity, a similar activity level in the longitudinal and lateral cyclic controls predictions and a slightly higher level of activity than the real pilot on the pedals.

The use of the "hysteresis" nonlinear element allows a more realistic prediction of the pilot's action in the controls, especially in the collective and pedal (stepped nature shape). However, this element has a collateral effect of modifying the trajectory tracking. So it is necessary to have a trade-off between good prediction level of the controls and the guidance prediction error.

Regarding the helicopter model (linear or "semi-linear"), it is not verified differences in the quality of the pilot's controls and flight path predictions that would justify the use of more complex model. Thus, all the identified pilot models incorporate linear model around 0 kt flight condition.

This choice aims to simplify the model and to reduce the computational effort, besides facilitates their extension and application in a real-time environment and on other types of aircraft models.

The pilots with low controls' activity for performing the maneuver or less aggressive piloting strategy (i.e., lower frequency and magnitude of controls to accomplish the same task) represents the most difficult scenario to identify the pilot model.

The basic SYCOS model does not allow a good tradeoff between predictions of controls and trajectory tracking, whenever there is a low pilot's activity in some control axis (even with the incorporation of nonlinear elements as "dead-zone" and "hysteresis"). This fact is evidenced in Figure 8, in which an almost no action on the pedals is associated to a low amplitude and frequency movement prediction.

7.1.2. Approach Tasks

7.1.2.1. Process

The process to calibrate the pilot model from the approach piloted simulations is slightly different from the hover one because of the introduction of the stability line (extended SYCOS model).

As in the hover training process, it starts by a preliminary selection of the inverse matrix and helicopter model (linear or "semi-linear") with fixed crossover gains and null all other SYCOS model parameters (including the stabilization ones), in a short term flight (around 15 sec).

Once selected, keeping constant all parameters, it rises the flight time interval to find the beginning of the divergence of the basic SYCOS model. For all approaches from training data set, this occurred over then 40 sec of flight prediction, and initially in pitch and roll axes.

From the moment that the prediction becomes unstable, adjust the stability line gains in order to recover stability of the model with the lowest values of these gains (by trial and error). The crossover gains, stability gains and the inverse matrix model are also modified in order to allow the stabilization of the system response, as well as providing preliminary adjustments in the quality of the prediction.

This method is applied for both extend SYCOS model proposals: attitude and acceleration feedback parallel lines.

After recover the pilot response stability, the flight prediction interval may be gradually extended until the total flight time of each task. Following, set again the crossover and feedback gains to obtain satisfactory values of pilot's controls activity and flight path predictions. Depending on the response, one may also readjust the inverse matrix.

Keeping all other guidance line parameters at zero (namely, dead-zone, time delay and hysteresis), the attitude feedback gains are introduced in the optimization process.

The optimization process for the approach tasks is:

a) minimize longitudinal and lateral cyclic prediction errors by optimizing crossover gains in u and v axes and attitude feedback gains ($K\phi$ and $K\theta$);

b) minimize collective prediction error by optimizing the crossover gain in w axis; and

c) minimize pedal prediction error by optimizing crossover gain in $\dot{\psi}$.

Once optimized one crossover or attitude feedback gain, this is considered fixed for the next stage of optimization.

After the optimization process, the crossover and feedback attitude gains are fined adjusted. By trial and error, it ends up the calibration process of the pilot's controls activity model to approach tasks by adjusting the other guidance line parameters.

Once more, the definition of the pilot's activity model is not only based on the prediction curve fit of the controls and flight path, but also in the capacity of providing useful pilot's activity information (sum of the mean DIMSS PM in all control axes).

7.1.2.2. Results

From the moment that the prediction becomes unstable and begins the stability recovery of the system through the stability line, it allows to analyze the capacity of each extension proposals (applied to different types of pilot's strategy and in high turbulence environment conditions).

The attitude feedback allows restore pilot's model prediction stability in all studied cases with slightly lower than 1 values of the attitude stability gains.

However, the acceleration feedback does not recover the stability or does not maintain the stability around the trajectory throughout the flight time of each task. This method causes only a time delay on the prediction instability beginning, followed by the same divergence prediction response or by a numerical divergence in the calculus (independent of the type of solver used).

In none of the cases, it is able to perform the approach task and maintain the helicopter stable throughout the range of the flight when using the proposed acceleration feedback.

For the approach tasks training data base, the attitude feedback method is the only that allows to stabilize the prediction of the SYCOS model without instability in the full flight time. Therefore, this study focuses on the modeling the pilot's controls activity by extended SYCOS with attitude feedback stabilization line.

Additionally, whatever the stabilization feedback strategy, the stability of prediction is not recovered when using the "semi-linear" helicopter model. Thus, all results presented herein use the helicopter linear model.

Table 5 presents the identified SYCOS model with an extended attitude feedback line for predicting pilot's control activity of approach tasks.

Table 6 presents a comparative between the DIMSS PM values of the pilot-in-the-loop flight data and its respective identified extended SYCOS model.

Figures 10 and 11 present an example of results of the pilot's activity model identified for the simulated "fore/aft" approach of pilot D.

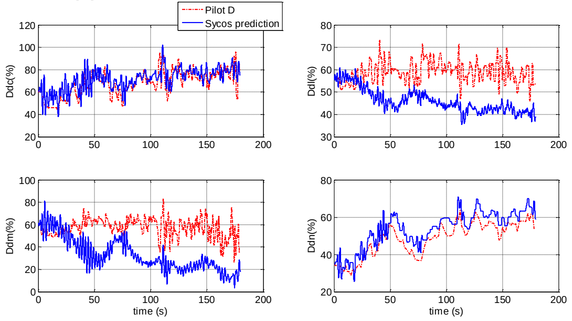

Figure 10. Prediction of pilot's controls activity of "fore/aft" approach training data set.

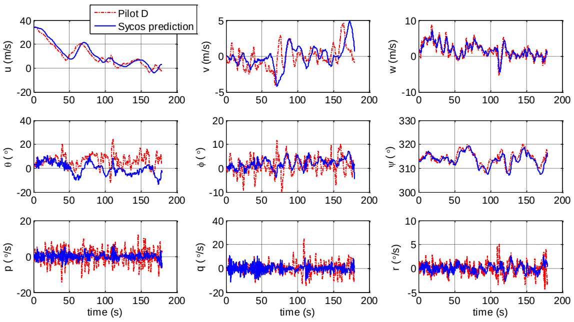

Figure 11. Prediction of state variables of "fore/aft" approach training data set.

As the flight time of the approach tasks are higher than 100 sec, the pilots have been subject to atmospheric disturbances longer than in hovering task.

In addition, they performed three mission task elements with different levels of workload when flying the same approach task. This made the pilots of "soft" piloting strategy to improve their actions at certain times of the maneuver, resulting in a more aggressive strategy than appeared in hovering task.

Thus, the identification of the pilot's controls activity is easier than to hover task, even with the introduction of the stabilization line gains.

The curves presented in Figure 10 represents the general behavior of controls movements' prediction for all pilots.

Despite the fact of using a linear dynamic helicopter model, it is observed a satisfactory prediction of flight path tracking and a good agreement in the collective and pedal activity, including the change of trimming position during the maneuver.

The prediction of the lateral and longitudinal axes of the cyclic are shifted when compared to the piloted simulation (however, it follows the trend). The prediction of the lateral demonstrates lower amplitude levels than the actual motion. However, it results in a similar pilot's controls activity of the piloted trials, as presented in Table 6 by the DIMSS PM level.

These remarks are valid for both types of simulation approaches ("fore/aft" and "estern").

In addition, the results of the pilot's controls activity prediction are qualitatively similar to those found in several published papers for the basic SYCOS model when performing tasks under turbulent environment (presented in references [7], [11] and [12]).

However, the results of this study come from the implementation of an attitude feedback line, providing an additional pilot strategy to the pilot and keep the predictions stables to a long term in high turbulence conditions (above 100 sec).

In addition, it uses a linear helicopter model that, although the simplicity, is able to provide realistic pilot's control activity results for the tested data. This feature is desirable for designing a "generic" pilot model, which may be able to perform high workload tasks in different aircrafts dynamics by using a simplified model.

7.2. Validation Process

The controls activity models identified for each pilot, presented in Tables 3 and 5, are used to predict the flight path and the respective controls' inputs for the validation data set.

As the main objective of this study is to identify the pilot control's strategy in order to provide prediction of controls' activity, the following validation criteria is applied to them:

- -accuracy: how well the model correlates an outcome (curve fit);
- -reliability: the capacity of the model in providing the same type of prediction or the same pattern, regardless the test data; and
- -usefulness: capacity of providing useful information

(in this case, the measure of the pilot's controls activity by means of DIMSS PM metrics values).

In addition, as the human pilot model may be able to satisfactorily perform the tracking task, the results of the flight path curve fit are also analyzed.

As for the training process, validation is divided into two tasks: hover and approaches.

7.2.1. Hover task

The identified activity models of pilots A and B, in general, result in predictions with good adherence to controls performed by pilots, for the three flight conditions of validation data. The tracking of the flight path performed by the pilot is also satisfactory, with small deviations from the flight data.

Figures 12 and 13 show an example of the validation data set results for the pilot B.

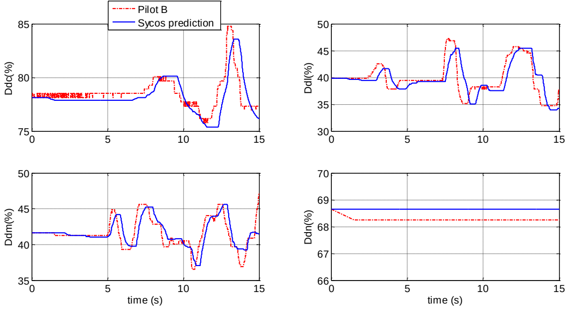

Figure 12. Prediction of pilots controls activity of hovering at 15 kt left crosswind.

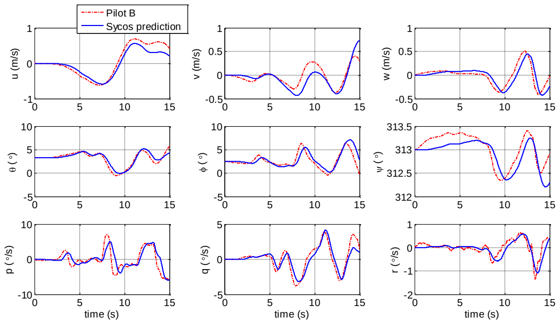

Figure 13. Prediction of state variables of hovering at 15 kt left crosswind.

The activity models of the pilots A and B provide even better adhesion of predicting flight path if the values of nonlinearity elements were removed from the models in all the all validation cases (as shown in Figures 14 and 15). However, the collective and cyclic predictions would not be able to predict the "stepped" piloting technique in these controls and it also provides unrealistic small amplitude and high frequency oscillations predictions to the pedals.

Likewise, these models have been able to provide reliable results, concerning the similarity to the real flight controls movement, regardless the validation data set.

From Table 4, it may note that the identified models of the pilots A and B for the hovering flight condition are able to provide closer and consistent predictions values of the mean DIMMS PM when compared to the real piloted ones. Besides, the predicted DIMMS PM values maintain the relative difference between each tasks condition, allowing the use of its prediction as workload predictor.

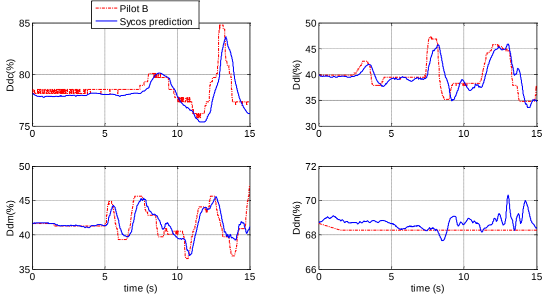

Figure 14. Prediction of pilot's controls activity of hovering at 15 kt left crosswind without hysteresis behavior.

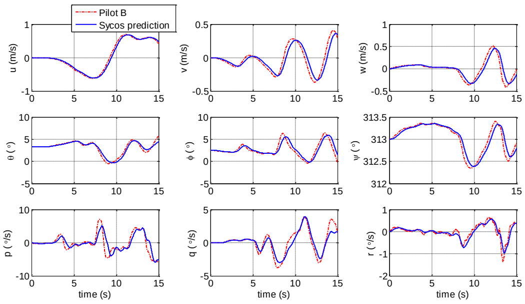

Figure 15. Prediction of state variables of hovering at 15 kt left crosswind without hysteresis behavior.

Therefore, the pilot's controls activity models for pilots A and B are valid to predict the requested hover tasks.

The pilots C and D present "soft" piloting strategy in the training data, confirmed by the crossover gain values being lower than those of pilots A and B (see Table 3). This feature is also presented in the validation data set. In some flight conditions, this type of piloting strategy makes temporary loses of the horizontal position of the aircraft, resulting in a degradation of the achieved performance (unlike the pilots A and B, which always maintained the desired performance level during the task time).

Additionally, it is noticed that both pilots C and D altered their piloting strategy throughout the tests (gradual increasing of movement in some axes, such as the longitudinal cyclic and the collective). This may be explained by better adaptation to the proposed tasks and to the aircraft's handling qualities, since these pilots needed more time to adapt to the flight simulator than the pilots A and B.

As a result, the models identified for pilots C and D neither permit a good fit of the prediction for the validation data set nor provide reliable predictions, in the frame of the quality of the results being very dependent to the flight condition.

In addition, for the pilot C, the low control's activity values, especially in the collective and pedals, reflects in low DIMSS PM values (low workload).

Although the behavior is also predicted by the identified model, the DIMSS PM predicted are not consistent to all validation data set conditions.

Figures 16 and 17 present an example of control's activity and state variables prediction for Pilot C model.

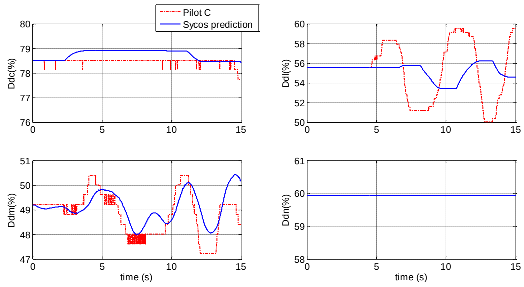

Figure 16. Prediction of pilot’s controls activity of hovering at 20 kt head wind condition.

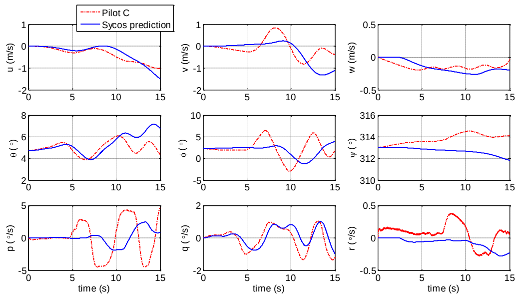

Figure 17. Prediction of state variables of hovering at 20 kt head wind condition.

The same may be observed for the pilot D model results, in which the low longitudinal cyclic activity strategy do not reflect the pilot strategy demonstrated in the training data set.

Thus, the controls activity models of pilots C and D cannot be validated for the validation data set.

7.2.2. Approach Tasks

The extended SYCOS model with the attitude feedback allows maintaining stable the prediction in all cases of the validation data set, regardless the pilot modeled.

Figures 18 and 19 present an example of the prediction results of pilot A model for “fore/aft” approach task.

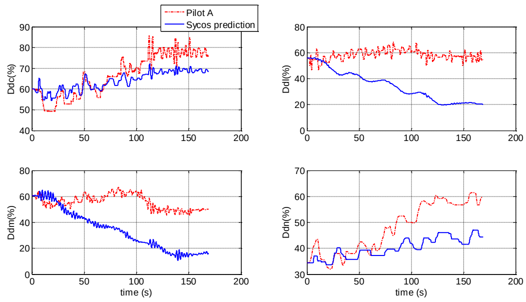

Figure 18. Prediction of pilot’s controls activity of “fore/aft” approach task at 20 kt head wind condition.

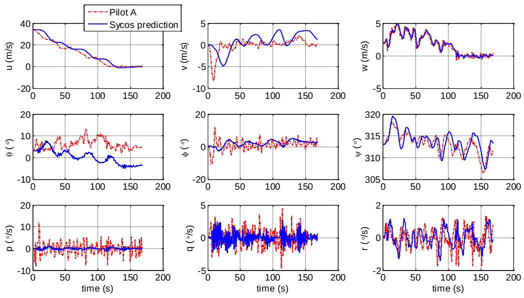

Figure 19. Prediction of state variables of “fore/aft” approach task at 20 kt head wind condition.

The identified pilot A controls’ activity model allows to recover the general trend of the movement of collective and pedal controls. However, the magnitudes of the collective control are underestimated when at low airspeed and there is a departure from the actual pedal trim position in relation to its prediction in all flight conditions (as presented in Figure 18).

In addition, as shown in Figure 18, the amplitudes of the cyclic predictions have always been underestimated and do not follow the same trend pattern of trimming command variation (for both longitudinal and lateral axes). For each flight condition, the prediction of the longitudinal and lateral cyclic controls have a different time history trend between them.

In this way, the accuracy of the cyclic control prediction is compromised, as its reliability.

Despite the problems presented in the prediction of the cyclic control movement, the relative variation of the mean DIMSS PM of pilot A follows the piloted simulation trend (Table 6). However, these values are not physical sensing, in view of the deficiency presented in the prediction of the cyclic activity.

Figures 20 and 21 present an example of the prediction results of the pilot B model for the “Estern” approach task.

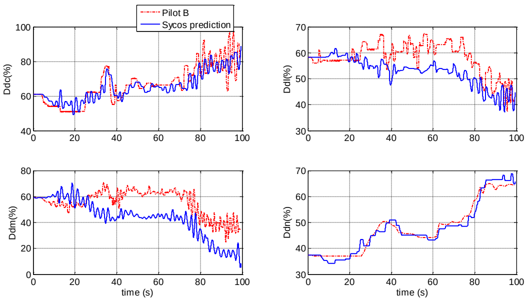

Figure 20. Prediction of pilot’s controls activity of “Estern” approach task at 0 kt wind condition.

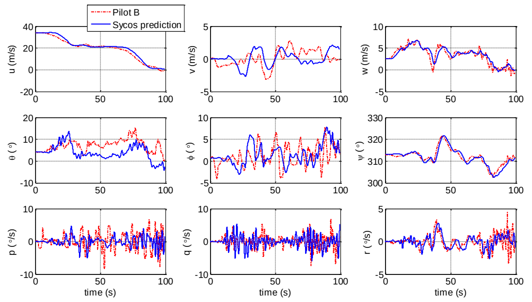

Figure 21. Prediction of state variables of “Estern” approach task at 0 kt wind condition.

The controls’ activity for the identified pilot B model allows a high accuracy of the pedals and collective controls movement, for all validation data set conditions.

The magnitude of the collective is underestimated around the hover flight (over 80 sec of flight), but always keeping the frequency of activity, as seen in Figure 20. However, the prediction of the pedals is able even to follow the command trimming trend, despite of using a simplified aircraft linear model.

Unlike the pilot A model, the prediction of longitudinal and lateral cyclic of pilot B activity always follow the actual trend of the pilot's movements with constant offset, regardless the validation data set. Still, it is possible to obtain similar magnitude and frequency values of these commands, and consequently, similar values of DIMSS PM metrics (Table 6).

For flight path tracking, the model of pilot B is able to keep the aircraft following the desired trajectory, with a slight error in the lateral velocity component, *v*, for all validation conditions. These features allow the virtual pilot to execute the desired trajectory of the "estern" approach similar to the real one.

Therefore, the controls activity model for pilot B is capable to provide reliable predictions with satisfactory level of accuracy for the validation data set.

Figures 22 and 23 present an example of the prediction results of the pilot D model for the “fore/aft” approach task.

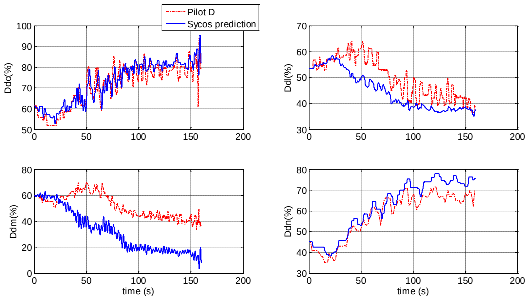

Figure 22. Prediction of state variables of “fore/aft” approach task at 15 kt left crosswind condition.

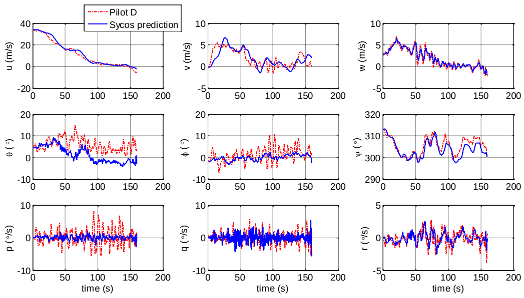

Figure 23. Prediction of state variables of “fore/aft” approach task at 15 kt left crosswind condition.

As for the pilot B, pilots C and D models provide a high level of curve fit between the control’s prediction and the actual pilot’s activity for the collective and pedals. This statement is valid for all of validation data set and is illustrated in the example shown in Figure 22.

However, the same quality of prediction is not obtained for the lateral and longitudinal cyclic activities.

The magnitude of the lateral cyclic is always underestimated, in order to not allow recovering the same level of pilot activity on this command. For the longitudinal cyclic control, the prediction is always more oscillatory than the actual pilot activity. Figure 22 shows a typical result of these control predictions.

Allied to this fact, the trimmed position trend of the cyclic control is not reliable, for the validation data set.

This cyclic prediction problem has directly affected the pilot's activity measurement, as presented in Table 6, which it does not present robustness for all flight conditions.

For the specific case of the pilot C, the identified pilot model provides still low adherence level on the flight path tracking, especially in *u* and *v* axes.

Thus, the extended SYCOS model with attitude feedback strategy identified for pilot B controlling activity is valid and for pilot A is not valid.

In the case of pilots C and D models, the validation is not possible because of the low reliability of their predictions of the cyclic controls activity (longitudinal and lateral axes). On the other hand, the prediction of the pedal and collective controls activity allow the use of models, depending on the application (for example, in the case of obtaining control’s margin or pilot’s controls activity only on these axes).

Finally, from this work, the extend SYCOS model with attitude feedback model identified for pilot B controls’ activity is the only one valid for the approach type "estern". None pilot’s controls activity model is valid for the "fore/aft" approaches. The pilots C ("estern" approach) and D ("fore/aft" approach) extended SYCOS models are able to provide satisfactory predictions only for collective and pedals activities.

8. CONCLUSIONS

The pilots' controls strategies are identified in order to provide prediction of positions of the controls when flying typical on-shore representative shipboard maneuvers, namely, hover and approach.

The basic SYCOS model is enough to follow the desired trajectory and still allow the studies of the prediction of pilot activity of hovering task, without instabilities.

Pilot A and B models are considered valid for hovering task. However, the identified models for the pilots C and D are not possible to be validated, in view of the low reliability of their longitudinal and lateral cyclic predictions.

For the approach tasks, the basic SYCOS pilot model does not keep the aircraft stable around its required flight path over 50 sec of flight time.

In this work, it is studied extensions to the basic SYCOS model by implementing an attitude or an acceleration feedback parallel line, in order to provide stability strategy to the pilot's controls activity prediction.

The attitude feedback line is the only method that allows introducing stability in the predictions of the SYCOS model for the training data. Consequently, it is the method of choice capable of pilot's activity model identification for approaching maneuvers.

The extended SYCOS model with attitude feedback strategy is used for training and allows the validation of pilot's activity model to "estern" type approach (pilot B) and none for the "fore/aft" type approach. The pilots C ("estern" approach) and D ("fore/aft" approach) extended SYCOS models are able to provide satisfactory predictions only for collective and pedals activities.

9. FUTURE WORK

Suggestions for further investigations following this research include:

- analyze the sensitivity of the validated models when changing the handling qualities and/or performance of the aircraft;
- examine the validity and robustness of the extended SYCOS model with attitude feedback line against dynamic interface data from *PycsHel* flight test simulation trials; and
- analyze changes in the basic SYCOS model in order to facilitate the identification and validation of "soft" piloting strategies, "fore/aft" approach tasks and when using non-linear helicopter models.

10. ACKNOWLEDGEMENTS

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Table 2 – Land-based mission task maneuvers description and required performance levels.

Task	Maneuver detailed description	Performance	
		Desired	Adequate
Hover	Maintain a 15 sec of 20 ft AGL stabilized hover (Maintaining the longitudinal and lateral position).	Inner hover target Heading ± 5°	Outer hover target Heading ± 10°
"Fore/Aft" Approach	Initiating from a stabilized level flight at 300 ft AGL and 2,0 km far from hover point, perform the approach profile keeping constant heading. Stabilize in hovering flight over the left square.	Heading ± 5°	Heading ± 10°
	Perform a lateral acceleration to the right square followed by a deceleration to achieve the inner hover target within 5 sec once the reference symbol is aligned to it. Complete the maneuver up to 20 sec from the lateral departure.	Heading ± 5° <1 overshoot from inner target	Heading ± 10° <2 overshoot from inner target
	Maintain a 10 sec of 20 ft AGL stabilized hover (Maintaining the longitudinal and lateral position).	Inner hover target Heading ± 5°	Outer hover target Heading ± 10°
"Estern" Approach	Initiating from a stabilized level flight at 300 ft AGL and 2,0 km far from hover point, perform the approach profile keeping constant heading to the right square.	Heading ± 5°	Heading ± 10°
	Continue the approach profile and initiate the deceleration to attain hover over the square and to achieve the inner hover target within 5 sec once the reference symbol is aligned to it.	Heading ± 5° <1 overshoot from inner target	Heading ± 10° <2 overshoot from inner target
	Maintain a 10 sec of 20 ft AGL stabilized hover (Maintaining the longitudinal and lateral position).	Inner hover target Heading ± 5°	Outer hover target Heading ± 10°

Hover "Fore/Aft" Approach "Estern" Approach

Figure 3. Images of the maritime representative land-based tasks executed at *PycsHel* simulation facility.

Table 3 – Identified basic SYCOS model for predicting pilot's control activity of HOVERING TASK (1).

Pilot	Crossover gain (*K*)				Time Delay (sec)				Dead-zone (m/s or °/s)				Hysteresis (%)			
	u	v	w	$\dot{\psi}$	u	v	w	$\dot{\psi}$	u	v	w	$\dot{\psi}$	Ddc	Ddl	Ddm	Ddn
A	3,0	1,6	2,0	1,5	0	0	0	0	0	0	0	0	1	1	0	5
B	5,0	3,0	3,0	3,0	0	0	0	0	0	0	0	0	1	1	1	4
C	1,0	0,5	1,3	0,3	0	0,2	0,2	0	0	0	0	0	1	1	0	3
D	0,5	1,0	2,0	1,0	0	0	0	0	0	0	0	0	2	1	2	3

(1) the helicopter model and the inverse matrix model are linear at 0 kt for all pilot models.

Table 4 – Real pilot and identified basic SYCOS model mean DIMSS PM Values for HOVERING TASK.

Data		Pilot A		Pilot B		Pilot C		Pilot D	
Set	Condition	DIMSS Actual	DIMSS Predicted	DIMSS Actual	DIMSS Predicted	DIMSS Actual	DIMSS Predicted	DIMSS Actual	DIMSS Predicted
Training	20 kt head & turbulence	30,0	37,0	67,2	74,6	19,6	22,69	70,5	69,2
Validation	20 kt head	4,3	4,3	2,9	1,6	2,8	0,7	5,7	2,6
	0 kt	11,0	6,4	3,1	4,2	0,4	0,3	2,7	1,0
	15 left	12,0	8,0	8,4	6,6	0,6	0,3	12,0	6,8

Table 5 – Identified EXTENDED SYCOS model with attitude feedback for predicting pilot's control activity of APPROACH TASKS (2).

Pilot	Inverse Matrix	Crossover gain (*K*)				Time Delay (sec)				Dead-zone (m/s or °/s)				Hysteresis (%)				Stability Gain	
		u	v	w	$\dot{\psi}$	u	v	w	$\dot{\psi}$	u	v	w	$\dot{\psi}$	Ddc	Ddl	Ddm	Ddn	$K\phi$	$K\theta$
A	10 kt	0,2	0,1	0,8	0,6	0,2	0,2	0	0	2	2	0	0	1	1	0	3	-0,5	0,8
B	30 kt	1,0	0,7	0,5	1,0	0,2	0,2	0,2	0	2	2	0	0	1	1	0	4	-0,2	0,5
C	30 kt	0,2	0,2	0,8	0,8	0,2	0,2	0	0	5	5	2	0	1	1	0	3	-0,2	0,2
D	30 kt	0,2	0,2	0,8	0,6	0,2	0,2	0	0	0	0	0	0	1	0	0	3	-0,2	0,4

(2) the helicopter model is linear at 0 kt for all pilot models.

Table 6 – Real pilot and identified EXTENDED SYCOS model mean DIMSS PM Values for APPROACH TASKS.

Data		Pilot A (fore/aft task)		Pilot B (Estern task)		Pilot C (Estern task)		Pilot D (fore/aft task)	
Set	Condition	DIMSS Actual	DIMSS Predicted	DIMSS Actual	DIMSS Predicted	DIMSS Actual	DIMSS Predicted	DIMSS Actual	DIMSS Predicted
Training	20 kt head & turbulence	22,6	21,3	29,7	31,3	10,7	12,2	25,9	31,4
Validation	20 kt head	6,6	3,8	16,6	13,7	3,6	1,1	6,9	4,8
	0 kt	7,0	4,1	17,4	14	6,5	6,4	12,3	8,4
	15 left	6,3	3,7	9,5	7,8	2,3	1,4	9,2	6,7