THE USE OF SIMULATION TOOLS TO ESTIMATE SHIP/HELICOPTER OPERATING LIMITATIONS - PILOT MODEL AND WORKLOAD PREDICTION COMPONENTS

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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 propose a methodology to establish an acceptable human pilot effort to perform ship-helicopter operations by means of pilot's controls activity measurements. For this, two metrics to predict pilot's workload are assessed: DIMSS PM and a modified power frequency (so called, cumulative power frequency). Operational pilots performed pilot-in-the-loop test simulation trials, in the helicopter engineering simulator facility of ONERA Salon de Provence Center, so called *PycsHel*, under realist frigate-helicopter operation models and scenario. The workload changes coming from ship-helicopter influential factors are reflected in the pilot's controls activity and that is well captured by both metrics. It is proposed a methodology to establish a safe human pilot effort boundary and both metrics provided consistent and conservative results when compared to the DIPES ratings assigned by the pilots. In addition, this paper also analysis the identified pilot's controls activity models, later developed from a land-based simulated environment tests, which work properly to what they were designed: to follow the movement of a target (the ship) without computing the ship's airwake. Therefore, after a preliminary modification on this pilot model, a new pilot model is suggested and validated, which is able to provide reliable and useful pilot's controls activity predictions, and consequently, workload metrics predictions, when under ship's airwake effect.

Symbols and abbreviations

Ddc, Ddl, Ddm, Ddn	Collective, lateral cyclic, longitudinal Cyclic and pedal positions
DIMSS PM	Dynamic Interface Modeling and Simulation System Product Metric
DIPES	Dynamic Interface Pilot Effort Scale
GVE	Good Visual Environment
$G_{\delta\delta}$	Single-sided power spectrum
ISA	International Standard Atmosphere
MTE	Mission Tasks Elements
MTOW	Maximum Take-Off Weight
OW	Operational Weight
PIO	Pilot-Induced Oscillations
PycsHel	Prototype and Design of Helicopter Systems
RMS	Root-mean-square
SAS	Stability Augmentation System
SL	Significance Level
u, v, w	Helicopter ground velocity components about fuselage x-, y- and z- axes.
ue, ve, we	Helicopter ground velocity components about Earth referenced axes.
W	Weight of the helicopter
WOD	Wind-Over-Deck
Xe, Ye, Ze	Helicopter ground positions components about Earth referenced axes.
μ	Mean of the population
σ	Relative density
Φ, θ, ψ	Euler angles defining the orientation of the aircraft relative to the Earth
$\dot{\psi}$	Yaw angle first differentiation with respect to time
ω_{cutoff}	Cutoff frequency
ω_{cum}	Cumulative power frequency
ω_G	Power frequency

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 this 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 testing, is the only approved means available at present [2].

Actually, recent models demonstrate good capabilities in capturing the major flight conditions including flights cases close to the limit or operational flight envelopes. 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 ONERA Salon de Provence center.

A research work is in progress to use these modeling and simulation tools to establish a methodology to predict helicopter maritime operating limits (oil rigs and vessels), to be used as a support tool to at-sea flight tests preparation and completion.

The proposed technical approach is to use offline simulation tools incorporated by a human pilot model, a workload predictor and some objectives criteria to develop a *Candidate Flight Envelope*.

The use of quantitative workload measurements in conjunction with qualitative ratings may provide a better and more effective means for defining a flight envelope. For this, it is necessary to select measurable quantities, or metrics, that may provide a robust indication of pilot's workload.

Studies have been developed in order to quantify pilot workload by directly measuring the pilot's controls activity. This approach offers various advantages from providing a quick and efficient method for assessing new systems or modifications to existing ones to providing additional information to support at-sea flight test activities.

The *Dynamic Interface Modeling and Simulation System Product Metric* (DIMSS PM) was first developed by Roscoe and Wilkinson [3] for evaluation of helicopter ship deck landings. Several studies have shown correlations of this metric to subjective workload ratings and handling qualities ratings during tests where turbulence is the driving factor for workload (References [4] and [5]).

More recently, Lampton and Klyde [6] studied the power frequency, one metric derived from cutoff frequency via wavelet analysis, based on fixed wing flight test data from an offset approach and landing task. They found strong correlation between the handling qualities ratings and the pilot input power frequency.

In this context, this paper presents the progress in designing a methodology to establish a safety operating limitation to ship-helicopter operations. The workload assessment by means of pilot's controls activity measurements is presented. For this, the above workload prediction metrics is analyzed and verified the impact of the influential parameters, in order to set an acceptable human effort to perform dynamic interface procedures (i.e., establish a criteria of safe workload).

In addition, this paper complements the results of Ref.7 by analyzing the validity and robustness of the identified pilot's controls activity models, developed from a land-based simulated environment, against a representative at-sea operational scenario test data.

2. SIMULATION ENVIRONMENT

2.1. *PycsHel* Overview

The rotorcraft engineering fixed-base 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 fully open and modular test bench facility dedicated to assist helicopter systems researches.

The *PycsHel* test bench facility consists of:

- four-channel collimated visual projectors able to provide a horizontal field of view of 265° and a vertical field of view of 135°;
- 2 side-by-side arranged seats in the internal configuration of a typical helicopter cockpit (left seat: classical rotary wing controls sticks);
- 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;
- off-the-shelf packages of *SundogTM* Software capable of providing real-time physical accurate environment effects (namely: sky, cloud, weather and ocean); and
- state-of-the-art non-linear realistic aircraft flight models (helicopters and Unmanned Air Vehicles), ship dynamic and environment models (namely: turbulence, ship airwake, and sea).

Figure 1 presents the cockpit interface of *PycsHel*.

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

2.2. Dynamic Interface Models and Elements

The aircraft model is a realist heavy-helicopter nonlinear-aeromechanics one, with a simplified SAS (*Stability Augmentation System*) incorporated, able to easily set the gains.

The ship visual simulation element is a representative frigate, in terms of sizing and deck markings, equipped with standards *Horizon Reference System* and *Stabilized Glideslope Indicator*. In addition, the ship deck dynamics model is based on a standard deck motion data for a generic frigate type ship under different levels of sea-state.

The aiwake is modeled with a spatially non-uniformly distributed mean disturbance derived from wind tunnels test data of a generic frigate model. This airwake can effects directly the center-of-gravity of the helicopter.

3. PILOT-IN-THE LOOP SIMULATION TRIALS

Late December 2015, four operational pilots from Brazilian Armed Forces performed a pilot-in-the-loop test simulation in *PycsHel* facility, in order to gather enough data for continuing the development, analysis and validation of this research project.

Table 1 presents a summary of the pilots' operational experience.

Table 1- Summary of operational background of the pilots.

Background	**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 landings	None	180	None	130

During these trials, the pilots executed recovery procedures into a representative maritime environment scenario and over a moving frigate, by using the most realistic ship (motion and air wake) and sea models of ONERA able to turn in real-time.

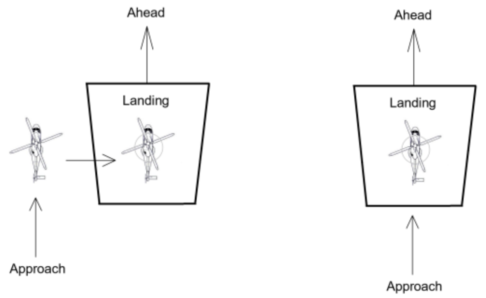
It was executed a total of 158 approaches and landings procedures in a GVE (*Good Visual Environment*) scenario at sea level and ISA+15.

Figure 2 presents some images of these tests.

Figure 2. Images of the at-sea simulation tests using the ONERA *PycsHel*.

It was followed the classical at-sea flight test procedure and the pilots assigned DIPES - *Dynamic Interface Pilot Effort Scale* (Figure 3).

As different landing procedures are used to increase the operational flexibility of the helicopter on board ships [8], it was tested the following procedures to be assessed: Fore-aft and Astern (Figure 4).



Fore-aft Astern

Figure 4. Schematic representation of the types of approaches tested (adapted from [8]).

Table 2 presents the MTE (*Mission Tasks Elements*) defined for both "Fore-aft" and "Astern" approach types.

The simulations were performed in different conditions of influential parameters, in order to assess their effects on the piloting control's strategy and workload (Table 3).

Table 3 - Summary of the tested conditions.

Aspect	**Parameter**	**Tested Conditions**
Operational	Approach type	Fore-aft and Astern
Helicopter	Weight	Maximum Take-Off Weight (MTOW) and Operational Weight (OW)
	Handling Qualities	SAS Alternative SAS Baseline SAS Reduced Baseline SAS OFF
Ship	Deck Movement	Sea state 4, 5 and 6. (1):
	WOD	Intensity: 0 kt to 70 kt Direction: -25° to +25°(2):

(1) Sea state definition of the Douglas Sea Scale.

(2) Relative wind direction definition: 0°, the wind blows from the "nose of the ship", "negative azimuth" the wind blows from the left of the flight deck and "positive azimuth" the wind blows from the right of the flight deck.

4. WORKLOAD PREDICTION METRICS

In the context of establishing a safe workload limitation to ship-helicopter operations by means of pilot's controls activity measurements, the objective is to validate a metric capable of:

Based only on the flight controls measurements, define a boundary of acceptable pilot's effort level to perform a Dynamic Interface procedure, in a robust, efficient and simple way.

As a consequence of these requirements, based on the results of previews studies, as well as on the ability to consolidate the information from all flight controls in a single parameter, it was selected the metrics DIMSS PM to be analyzed.

In addition, following the same spirit, it's suggested a new metric derived from the power frequency to be analyzed and so called *Cumulative Power Frequency*.

4.1. DIMSS PM

According to Ref. [3] the DIMSS Product Metric is defined as the product of the number of control reversals (a minimum or a maximum in the control deflection time history) and the standard deviation of control deflections in a moving three-second window. The window is shifted at the sampling rate (i.e. every 0,01 seconds).

The premise of the DIMSS PM is that high frequency (large number of control reversals), large amplitude control movements, resulting in high values of the metric, represented high pilot workload. Similarly, low frequency, low amplitude control movements, resulting in low values of the metric, represented low pilot workload [3].

Being physically consistent with the human pilot features, the reversals at frequencies higher than 3,3 Hz are filtered out, as reversals above this frequency are not considered to reflect pilot workload [3].

The sum of the DIMSS PM time histories across all 4 control axes are calculated and result in a new time history vector, which consolidates all control's movement in single parameter. From this new time history, the mean, root-mean-square (RMS) and significant wave height (average of highest one-third of the data) of the sum of the DIMSS PM is calculated and analyzed.

4.2. Cumulative Power Frequency

The Power Frequency, which is derived from cutoff frequency via wavelet analysis, relates the frequency of pilot input with the intensity of that input. This metrics takes the following form at a given time instant:

(1) $$\omega_G = \frac{\omega_{cutoff}.\,max(G_{\delta\delta})}{1000}$$

However, according to Ref. [6], the maximum power frequency is dependent of the pilot who is rating the task. Thus, in this study, in order to reduce the pilot's influence on the values of power frequency, it is suggested to incorporate the accumulated energy in the whole range of frequencies in a defined time window. This proposal is called Cumulative Power Frequency, ω_{cum}, and defined as:

(2) $$\omega_{cum} = \frac{\omega_{cutoff}\cdot\frac{1}{2\pi}\int_0^\infty G_{\delta\delta}.\,d\omega}{10}$$

The metric is scaled by dividing by 10, an arbitrary term that is used to scale the parameter in the order reach the same order of magnitude of the DIMSS PM results.

In addition, it's selected the same windowing and analysis method of the DIMSS PM ones (a moving three-second window shifted at the sampling rate of 0,01 seconds).

Physically, the hypothesis behind this metric is that high frequency (high values of cut off frequency) and large amplitude of the controls in all frequencies (high cumulative energy level on the entire frequency range), result in high values of the metric, reflecting high pilot workload.

5. ANALYSIS OF THE WORKLOD PREDICTION METRICS

Given a ship, the limits of operation of a particular helicopter is function of the following parameters: approach type, referred weight (*W/σ*), deck movement (sea state), wind-over-deck (WOD), visual conditions and the handling qualities of the helicopter itself.

In addition, the pilots are asked to assign a qualitative comprehensive workload rating to perform each Dynamic Interface landing maneuver, based on aspects like: visual cues, pilot workload, flight control activity, aircraft attitude, ship airwake turbulence intensity and ship motion.

In this way, it is natural a dispersion among the ratings assigned by different pilots, by the intrinsic subjective analysis and the different pilot's strategies to accomplish the same task. Thus, the “pilot” may also be considered as an influential parameter in the definition of the operating limits.

The objective of this item is to verify the influence of these parameters in the pilot workload and whether this influence results in changing the pilot's control activity, being properly captured by the suggested metrics. Besides, to check the correlation of these metrics with the workload assigned by the pilots in terms of DIPES ratings.

5.1. Approach Type

In general terms, to same conditions (set of influential parameters), higher DIPES ratings (i.e., higher workload values) were obtained for fore-aft type approach than Astern (see Table 4).

This result is consistent with the comments of the pilots and confirmed by their difficulty in adapting to the approach type fore-aft (especially in maintaining the height and the formation flight when performing the MTE Transition).

This different workload level was reflected in the pilot' s controls activity, a fact that allows the use of the proposal metrics to predict workload. Also, it can be observed that the changing of the pilot's activity was correctly captured by these metrics.

Even in the MTE hover over the deck, it was observed higher level of pilot's controls activity in the approach type fore-aft than in Astern (evidenced by the results of the metrics presented in Table 4). This is justified by the fact that the transition in approach type Astern comes from a longitudinal stabilized condition (with well-defined visual references and heading).

5.2. Referred Weight of the Helicopter

As all tests were carried out under the same pressure-altitude and air density conditions, the influence of the Referred Weight is assessed by the simple variation of the aircraft's weight.

Table 5 shows examples of the influence of the aircraft's weight in pilot workload (DIPES assigned ratings).

In general, higher DIPES ratings were assigned in conditions of higher weight (MTOW). This result is coherent with the expected, considering that in conditions of higher weight some phenomena as restriction of power, margin and control' s response negatively affect the pilot's strategy. Because of that the classic Dynamic Interface flight test technique, the so-called *wedding cake* strategy is applied (in which the results for a higher referred weight are also valid for the lower referred weight and the latter do not have to be tested again [8]).

This change in workload level was accompanied, in all studied cases, by an increase in the amplitudes and/or the frequencies of aircraft' controls activity (depending on the piloting strategy and the SAS configuration). That was captured consistently, by both DIMSS PM and Cumulative Frequency Power, when compared to the ratings reported by the pilots.

5.3. Handling Qualities

The influence of different handling qualities was evaluated by adjusting the SAS gains, based on the limits for pitch (and roll) oscillations established on ADS-33E-PRF for hovering and low speed maneuvers [9]. Thus, according to the criteria of this standard, the handling qualities of the aircraft degrade in the following sequence: SAS Alternative, SAS Baseline, SAS Reduced Baseline and SAS OFF.

Table 6 shows an example of the influence of SAS settings.

The pilots always assigned higher DIPES ratings for more degraded handling qualities configurations. Furthermore, the change in the SAS configuration also modified the piloting strategy and pilot' s controls activity. And, in general, the degradation of handling qualities resulted in an increasing in the amplitudes of the controls, as well as in the cumulative energy level.

This fact was reflected in the values of the workload prediction metrics, except for SAS Reduced Baseline and SAS OFF configurations, in which the increase of the pilot workload was not accompanied by an increase of the controls activity (and consequently, increase of metric values). In these cases, it was observed undesirable lateral motions resulting from the pilot's action on the controls, when under flight-path constraints and in high feedback gain (PIO, *Pilot-Induced Oscillations*), requiring the pilot to reduce the inputs on the controls, especially in the lateral cyclic, in order to accomplish the task.

Thus, despite the increase of the workload in relation to the best flying qualities configurations, because of the PIO phenomenon, there was a reduction in the pilot's controls activity. This fact caused the low values of the prediction metrics, even in high workload condition.

Therefore, the metrics are able to predict the workload following the changes in the handling qualities of the aircraft, by only measuring the controls activity. However, the prediction of these metrics are not valid when tendency to PIO occurs.

5.4. Sea State

As expected, the rise of the sea state level results in an increase in DIPES ratings, to a same tested conditions.

Table 7 presents examples of the influence of the sea state.

The increase in movement of the ship provided by this rise of the sea level, increased the gain of the pilot to maintain the height over the deck as well as the lateral position. This resulted in an increase of the amplitudes of all controls of the helicopter, as well as the peak frequencies on both longitudinal and lateral cyclic stick.

Consequently, from this increasing in the pilot's controls activity, the values of both prediction metrics are consistent, when compared to the increase DIPES ratings assigned by the pilots, as can be seen in Table 7.

5.5. Wind-Over-Deck

As expected, under the same conditions, the workload increases whenever increases the intensity of the wind-over-deck in all tested azimuth range. And this workload increasing was followed by an increasing on the intensity and/or peak frequency of all flight controls.

For relative wind green direction (relative wind comes from the right of the ship), it was noticed change in the pilot's strategy when near to limit of left pedal (less inputs in this control and degradation in the performance level in maintaining the aircraft's heading).

In this context, it's remarkable the maneuver performed by the pilot D under WOD of 20°/60 kt, in which the pilot assigned DIPES 4 (excessive effort), based on the additional difficulty in performing the maneuver coming from the reduced margin of pedal (only 8% of margin). At this point, the activity in the controls was lower than that obtained in the other DIPES 4 conditions, due his change in piloting strategy. However, flight conditions like this one would be naturally excluded from the operating limitations because of the reduced margin of pedals.

5.6. Pilot

It was observed the following characteristics of pilots that took part of these trials:

- Pilot A: medium aggressive piloting strategy, that emphasizes the increasing in lateral cyclic amplitude for high workload conditions (peak frequency around 0,3 Hz);
- Pilot B: aggressive piloting strategy, that emphasizes the increasing in collective, pedal and longitudinal cyclic amplitudes for high workload conditions (peak frequency around 0,3 Hz); and
- Pilot D: soft piloting strategy, that emphasizes the increasing of the movement frequency of the lateral and longitudinal cyclic controls (peak around 1 Hz and 0.4 Hz, respectively), rather than their amplitudes, for high workload conditions.

Pilot C was only available to take part of the initial adaptation simulation trials. Therefore, it was not possible to acquire enough data to identify his piloting strategy.

Figures 5 and 6 present the average and standard deviation of the sum of the DIMSS PM and Cumulative power frequency time histories across all controls, for all hovering over the deck task performed by pilots.

The average of the sum of DIMSS PM, as well as the average of the sum of ω_{cum}, provided consistent results, that followed the workload trend represented by the increasing of the DIPES ratings assigned by each pilot (Figures 5 and 6).

It is observed in Figure 5 that, regardless the piloting strategy, it was obtained similar values of DIMSS PM metric for the three evaluated pilots, especially for the higher workload ratings (DIPES 3 and 4). This shows the robustness of the DIMSS PM metric regarding the different piloting strategies presented on this test trials.

However, the cumulative power frequency metric provided similar values only for pilots A and B, and much lower values for pilot D (Figure 6). This is justified by the fact that this pilot presents a piloting strategy based on the changing of the control's frequency rather than the amplitude (more concerned in stabilizing the aircraft over trajectory than to follow exactly the desired flight-path).

Thus, the cumulative power frequency estimative is more influenced by the change in amplitude than to the change in frequency of the controls activity.

6. METHODOLOGY TO ESTABLISH A SAFE WORKLOAD CRITERIA

In item 5 of this study, it was shown that the workload on a ship-helicopter operation is possible to be estimated by measuring the pilot's controls activity, and that both studied workload metrics are able to capture this change in the activity of the pilots.

From these metrics it is feasible to establish, at least, a boundary of maximum acceptable human effort (workload) once over the ship's deck.

Then, this work proposes a methodology to set an acceptable human effort to perform dynamic interface procedures.

Initially, for each at-sea tested condition, it shall be obtained:

a) Calculate the sum of the DIMSS PM (and ω_{cum}) time histories across all 4 control axes;
b) For this new vector, determine the average, RMS and the mean of significant wave height (average of the highest one-third of the data) for both metrics; and
c) Associate it with the DIPES ratings assigned by each pilot and the statistics obtained for each metric.

Figures 5 and 6 present examples of this statistics analysis results.

However, as the objective is to establish a boundary of the acceptable DIMSS PM and ω_{cum} maximum values, it is used the hypothesis test as a statistical inference method to that. In this case, the following sequence is suggested:

a) the statistics values (mean, RMS and wave) of each metric are divided into two subgroups per pilot:

- DIPES 4: containing only the DIPES 4 assigned ratings test points; and
- DIPES 3+4: containing DIPES 3 and 4 assigned ratings test points (conservative workload criteria).

b) verify the normality of each subgroup data by means of a normality test;
c) once confirmed the normality of the data, perform the mean population analysis test to compare data between pilots (check if the data belong to the same population). If the subgroups of each pilot do not belong to the same population it should be established workload boundaries for each pilot. Instead, it may be established a general boundary for groups of pilots (groups of piloting strategies).
d) Finally, for each subgroup of data, divided by pilot (or group of pilots), perform an upper tail hypothesis test of the population mean and set the most appropriate mean of population limit.

From this procedure, it can be set DIMSS PM and ω_{cum} limits of excessive workload, DIPES 4, or highest tolerable workload, DIPES 3+4, for each pilot (or group of pilots).

6.1. DIMSS PM

By applying the proposed methodology, it is proved, statistically, which can be seen in Figure 5: the DIMSS PM data set of all pilots belongs to the same population. Thus, it is possible to establish a general DIMSS PM safety limit criteria for the all three pilots together.

Table 8 presents a set of acceptable DIMSS PM workload limits stablished from the methodology presented in this work.

Table 8. DIMSS PM acceptable human pilot effort boundary established from all tested data.

Statistic property	Subgroup	Results: boundaries	
		99% SL	95% SL
Mean	Dipes 3+4	μ ≥ 66	μ ≥ 69
	Dipes 4	μ ≥ 78	μ ≥ 84
SUM RMS	Dipes 3+4	μ ≥ 73	μ ≥ 75
	Dipes 4	μ ≥ 85	μ ≥ 91
Wave	Dipes 3+4	μ ≥ 100	μ ≥ 104
	Dipes 4	μ ≥ 115	μ ≥ 123

Figure 7 presents a comparative drawn between the limits set out in Table 8 and the subjective assessment of the pilot B for the following flight conditions: fore-aft approach, MTOW, SAS baseline and sea state 5.

It is observed that all flight conditions assigned as excessive workload (DIPES 4) by pilot B are considered over the limit by DIMSS PM workload criteria, being also excluded some others conditions considered acceptable by the pilot (DIPES 2 or 3 ratings). Which indicates that the DIMSS PM is conservative regarding pilot's effort to perform the desired task.

This comment is valid for all pilots, except for Pilot D, who had assigned DIPES 4 for WOD 20°/60 kt, although the values of DIMSS PM statistics are below the limits established in Table 8 (for instance, Mean = 55,1). However, as stated before, this flight condition would be excluded of the operating limitations, because the margin of pedal is less than 10%, regardless of the pilot's workload assessment.

In general, the DIMSS PM metric points as acceptable pilot's effort the same WOD conditions, regardless the statistics used (mean, RMS or wave).

Additionally, the values of DIMSS PM are consistent and conservative when compared to the DIPES ratings assigned by the pilots.

6.2. Cumulative Power Frequency

By applying the same analysis methodology for the cumulative power frequency metric, unlike DIMSS PM metric, the type of piloting strategy influences the definition of workload limits, as well as the statistics selected (mean, RMS or wave).

In general, it has been found that the cumulative power frequency data, for the pilot D, are statistically different from data pilots A and B data (confirming the apparent difference shown in Figure 6).

It can be seen that the variation in the amplitude of the controls has stronger influence in defining the ω_{cum} values than the variation in frequency. Therefore, as pilot D presented a piloting feature of increasing the frequency of the actuation on the controls once in high workload flight conditions, the ω_{cum} results are lower than those of the pilots A and B.

Thus, it is established a boundary of acceptable workload for the pilots A and B, and one separate for the pilot D.

Table 9 presents a set of acceptable cumulative workload frequency values stablished based on the methodology presented in this work.

Table 9. ω_{cum} acceptable human pilot effort boundary established from all tested data.

Statistic property	Subgroup DIPES 3+4	Results: boundaries	
		99% SL	95% SL
Mean	Pilot A+B[(1)]	μ ≥ 65	μ ≥ 73
	Pilot A+B	μ ≥ 48	μ ≥ 52
	Pilot D	μ ≥ 24	μ ≥ 28
SUM RMS	Pilot A+B	μ ≥ 68	μ ≥ 72
	Pilot D	μ ≥ 21	μ ≥ 28
Wave	Pilot A+B	μ ≥ 99	μ ≥ 105
	Pilot D	μ ≥ 43	μ ≥ 50

(1) limits established for DIPES 4 subgroup data.

Figure 8 shows a comparative example between the ω_{cum} limits, presented in Table 9, and DIPES ratings assigned by pilot B to the same flight conditions of Figure 7.

Comparing Figures 7 and 8 is observed that, by applying a 99% Significance Level metrics limits, it is possible to highlight all test conditions assigned as DIPES 4 for both metrics.

However, the metric ω_{cum} is less restrictive than DIMSS PM, reducing the number of WOD conditions above the workload limits (this remark is valid for all pilots and statistics of the metrics analyzed).

Unlike DIMSS PM, the cumulative power frequency provides slight different predictions of the WOD conditions out of the safe limits boundary, depending on the statistics applied (mean, RMS or wave). In which the wave statistics presented consistent results with the DIMSS PM one.

As in DIMSS PM, the ω_{cum} values are consistent and conservative when compared with the DIPES ratings assigned by the pilots. However, its extension to several pilots (or group of pilots) is subject to the piloting strategy (frequency and amplitude of the controls use).

Finally, for both DIMSS PM and cumulative power frequency metrics, this workload analysis methodology would establish a safe human pilot effort, providing to the flight test team the "hot" flight test conditions in terms of the workload. It could also assist the preparation and the execution of at-sea flight tests, regarding the most appropriate sequence of test conditions execution (build-up approach).

7. PILOT'S ACTIVITY MODEL

Late 2014, the same pilots participated of a pilot-in-the-loop test simulation in *PycsHel* facility, in order to provide data to develop a preliminary pilot's control activity model. On that opportunity, it was established three land-based tasks representative of shipboard operations, and it was validated one pilot's activity model for hovering task for each pilot [7].

The general objective is to develop a dynamic control element that can replace the pilot-in-the loop simulations with representative control's strategy of human pilots (i.e., similar values of the workload predictions metrics). For this, this dynamic element shall be able to, at least:

Maintain 15 sec of stabilized hovering at 15 ft over the ship's deck and reproduces the human pilot's controls activity, in terms of DIMSS PM and ω_{cum} values, with high accuracy and reliability.

Then, in this item, the validity and robustness of the identified pilot's controls activity models, developed from land-based simulated environment and presented in Ref [7], against a representative at-sea operational scenario test data.

7.1. Pilot's Tracking Reference

First of all, it is necessary to check the parameters used by pilots as tracking reference in hovering, y_{ref}, during the simulated at-sea trials, and to verify their consistency with those used in the identified pilot models, namely:

(3) $$y_{ref} = [u\ v\ w\ \dot{\psi}]$$

The pilots were unanimous in choosing the ship's hangar roof as vertical, lateral and longitudinal movement reference.

Figure 9 presents an example of the ground positions and ground speeds of the ship's hangar roof compared with the ones registered on piloted simulation. Regarding the heading, it was noted that all pilots maintained the heading of the ship ± 5 °.

In general, the reference ground positions and speeds are followed by the pilots on the vertical axis (*Ze*, *we* and *w*) with good level of tracking accuracy (maximum time delay of 1 sec). While a higher delay (around 3 sec) and lower tracking accuracy level is presented for the longitudinal (*Xe*, *ue* and *u*) and lateral (*Ye*, *ve* and *v*) axes.

This fact can be justified by the lack of remarkable references to define movements in lateral and longitudinal axes of the ship (delay in detecting the movement), as well as, by the third order dynamics of cyclic controls while the collective is a first order dynamics (different command response).

Thus, the use of such tracking reference presented at Equation (3) is consistent with the manner seen by pilot to control the aircraft over the deck, in the tested conditions.

7.2. Identified Models Validity

The models of human pilot to maintain a stabilized hover are presented in Ref [7]. They were obtained from an adapted ADS-33 hovering task, for different wind conditions and atmospheric turbulence. Further, the helicopter model was linear around the hover flight condition, as well as the inverse matrix dynamics.

In all cases, it is observed that the pilot model is able to guide the aircraft following the desired vertical reference and heading, with good adherence level to these references.

The quality of tracking lateral and longitudinal ground speeds depends on the model's crossover gains (pilot aggression). For the pilot B, more aggressive one, the prediction of these parameters has good matching to the actual reference data, with a slight reduction of matching level on the end of the prediction time under intense controls activity conditions.

For pilots A and D, the predictions present good matching to the reference ground speeds up to about 10 sec of prediction, from which the matching is reduced incrementally over time (even starting to diverge). This effect is more intense with the increasing of the WOD intensity.

In terms of flight controls prediction, the collective lever position is correctly predicted in all cases.

The predictions of the longitudinal and lateral cyclic controls are always similar or higher, in terms of amplitude and frequency, than the actual ones, for the most aggressive pilots (pilot A and B). Even unrealistic predictions are obtained (exceeding 100% of the control) for intense airwake conditions.

Meanwhile, pilot D model provides similar amplitudes of longitudinal and lateral cyclic to the actual values of these controls, however, with higher frequencies of activity. The piloting strategy of pilot D is to increase the frequency of the cyclic control activity whenever in high workload flight conditions (this feature did not appear in the land-based simulation trials).

For the pedals, it is observed that the predictions of the pilots A and B models are always higher, in amplitude and in frequency, than the actual pedal's activity. However, pilot D model provides good predictions accuracy, for low intensity WOD conditions, that are degraded when under high intensity level of WOD.

There is not full divergence of the prediction in any of the studied cases (around 15 sec of stabilized hover each). However, for larger times, depending on the condition, the stability of the predictions is not guaranteed, as the identified models do not incorporate the stability feedback line (extend SYCOS model).

In order to verify the influence of the airwake on the controls predictions accuracy, some WOD conditions were piloted without ship's airwake model running (only movement of the ship). Table 10 presents some of these results.

Figures 10 and 11 shows an example of prediction results provided by the pilot B model under no airwake conditions.

The three pilot models are able to provide coherent and reliable predictions of DIMSS PM and ω_{cum} metrics (bias error type when compared to actual values), to flight conditions without any airwake turbulence.

This shows that the land-based scene with high turbulence modeling allows to model a pilot able to follow the movements of a moving platform and replicates the general activity in the helicopter's controls.

However, the pilot's controls activity predictions, and consequently, the workload metrics predictions, for pilots A and B, have low accuracy and reliability when under ship's airwake effect. When the controls activity is higher than that of training dataset ones, the pilot models provide unrealistic estimative of the longitudinal and lateral cyclic controls, with values reaching above 100% of these controls.

This may reflect the fact that the proposal land-based hovering task does not allow the pilots to apply the more appropriate piloting strategy when flying under airwake conditions over a confined ship deck. In addition, it could be emphasized by the fact that the pilot model incorporates a simplified helicopter linear model without the introduction of the external disturbances.

Thus, pilot A and B models work properly to what they were designed: to follow the movement of a target (the ship) without computing the external disturbances (airwake).

Meanwhile, pilot D model provides acceptable values of DIMSS PM under airwake flight conditions, but neither reliable nor consistent values with the workload ratings assigned by the pilot.

For the cumulative power frequency, although some stability issues regarding u and v references tracking appear, pilot D model provides coherent predictions with pilot's assigned ratings, even under airwake conditions. This fact is justified by the lower pilot's workload demand flight conditions (lower sea level and intensity of airwake) when compared with those flown by pilots A and B, besides by the fact that this metric is more affected by the prediction of the amplitude than of the frequency of controls activity (pilot D model provides predictions with similar amplitudes of the controls when compared to the real flight data).

7.3. Modifications on the Pilot Model

From the results herein presented, it proved the validity of pilot models to provide consistent and reliable pilot's controls activity results to maintain a stabilized 15 sec hover over a ship deck without airwake effects (only constant wind and ship movement effects).

Thus, it is proposed the following modifications to the pilot models and/or to the identification method, in order to improve the results when flying under ship's airwake conditions:

- introduce the developed attitude stability feedback line and relate it to the nearest trimmed conditions (to provide stability to the predictions in the whole trajectory);
- introduce the effect of the airwake on the helicopter's model of the pilot model; and
- set the state and command vectors initial values on the nearest trimmed conditions related to the current flight condition to be flown (to improve trajectory tracking and reduce instabilities issues).

By applying the above proposals, it is possible to train and validate, in a preliminary way, a pilot B model able to predict the pilot's controls activity under airwake conditions for hovering over the deck (flight conditions: fore-aft approach, SAS Baseline, MTOW and sea state 5). The identified mathematical model is shown in Table 11.

For this, four different WOD conditions is selected as training dataset: high and low dynamic pressure; high and low activity level pilot's controls.

The effect of airwake is modeled as a perturbation on the airspeed applied on the center-of-gravity of the helicopter, and this airspeed is the same of the piloted simulation one (independent of the aircraft's position prediction). For this, it is used a model called "semi-linear", composed of linearized flight dynamics around several level flight conditions, plus the nonlinear coupling of inertia, gravity and relative speed effects.

Table 12 presents examples of the predictions of the workload metrics from this pilot B modified model. Figures 12 and 13 present an example of its controls and state predictions.

In general, it is observed a bias type error in the predictions of the metrics on both training and validation dataset, which shows the reliability of the predictions. For the training dataset, the predictions of DIMSS PM are lower than the actual values (around -11), and of ω_{cum} are higher than the real values (around +9).

By applying these bias values in the predictions of both metrics for the validation dataset results (Table 12), and using the criteria set out in Tables 8 and 9, it is confirmed the capacity of this model in providing useful information regarding the acceptable human pilot effort boundaries established on this work.

For example, if the DIPES 4 limits are established as boundaries (over 84, for DIMSS PM, and over 73, for ω_{cum}), the same WOD conditions would be considered above the maximum acceptable pilot's effort (-10°/50 kt and 0°/20 kt) by both metrics. These results are consistent and conservative in relation to DIPES ratings assigned by the pilots, as seen in Table 12.

As the predicted trajectories are slightly different from the reference, especially in the longitudinal and lateral axes, besides the low accuracy of Φ and θ predictions, the predicted ground positions are not the same as the reference.

8. CONCLUSIONS

The present work reports a methodology to establish an acceptable human pilot effort to perform ship-helicopter operations by means of pilot's controls activity measurements.

The following metrics to predict pilot's workload are assessed: DIMSS PM and the modified power frequency (so called, cumulative power frequency).

In this context, the following conclusions have been drawn:

- the workload changes coming from influential factors (namely, approach type, referred weight, sea state, wind-over-deck and the handling qualities of the helicopter), are reflected in the pilot's controls activity and that this is well captured by the proposed metrics; and
- by applying the proposed methodology to establish a safe human pilot effort boundary, these metrics provided consistent and conservative results when compared to the DIPES ratings assigned by the pilots.

In addition, this paper complements the results of Ref.7 by analyzing the identified pilot's controls activity models, developed from a land-based simulated environment, against a representative at-sea operational scenario test data.

In this context, the following conclusions have been drawn:

- the use of helicopters ground speeds as tracking references is consistent with the manner used by the pilots to control the aircraft over the deck, in the tested conditions;
- the previews identified pilot models provide only good pilot's controls activity predictions when flying under no airwake effect; and
- by modifying the pilot model as suggested in this work, a new pilot model is validated, which is able to provide reliable and useful pilot's controls activity predictions, and consequently, workload metrics predictions, when under ship's airwake effect.

9. FUTURE WORK

Suggestions for further investigations following this research include:

- analyze the influence of the degraded visual conditions environment on the pilot's controls activity and, consequently, on the DIMSS PM and cumulative power frequency metrics; and
- continue the development and validation process of the human pilot models, to perform Dynamic Interface operations, by applying the suggested modifications presented on this work, and verify the impact of the ship-helicopter influential factors on it.

10. ACKNOWLEDGEMENTS

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Table 2. *Mission Tasks Elements* defined to the at-sea simulation trials.

MTE	Approach Type	
	Fore/Aft	**Astern**
Approach to an intended end point near to the ship maintaining around 3° of glide slope.	End point in the left of the ship's deck (around 30 m from the center line) and 50 ft ASL.	Perform a short approach up to the edge of the flight deck.
Hover (helicopter's longitudinal axis is parallel to the ship's center line)**.**	Alongside left to the ship's deck (around 30 m from center line) close to the ship and 50 ft ASL.	If necessary, close and behind to the ship's deck at 50 ft ASL.
Transition	Lateral transition across the deck (at level height) following the "bum-line" (helicopter pedals over it) up to center line.	Longitudinal transition across the deck (at level height) following the center line.
Hover over the deck*	Minimum of 10 sec station keeping at 15 ft above the deck, in line with the hangar roof and over the landing spot.	
Touchdown*	Vertical descent to touchdown (when ship in a quiescent state). Complete the landing in less than 5 sec.	

* DIPES ratings assigned take only this tasks as reference.

Table 4. Examples of approach type influence for Pilot A, SAS Baseline, MTOW and sea state 5.

Simulation Test Results			DIMSS PM			ω_{cum}		
WOD (°/kt)	**Approach**	**DIPES**	**Mean**	**RMS**	**wave**	**Mean**	**RMS**	**wave**
0 / 60	Fore-aft	3	76,8	81,5	105,4	57,2	62,9	85,2
	Astern	1	37,8	40,9	55,8	26,8	34,3	48,5
0 / 45	Fore-aft	2	73,3	78,3	104,6	52,7	64,2	91,3
	Astern	1	53,3	59,1	81,7	32,2	40,4	60,2

Table 5. Examples of weight influence for Pilot B, Fore-aft approach, SAS Baseline and sea state 5.

Simulation Test Results			DIMSS PM			ω_{cum}		
WOD (°/kt)	**Weight**	**DIPES**	**Mean**	**RMS**	**wave**	**Mean**	**RMS**	**wave**
-25 / 35	MTOW	4	94,3	100	132	87,5	100	142
	OW	2	52,9	57,9	81,4	45,6	57,1	84,4
10 / 50	MTOW	3	82,1	86,7	114,6	52,3	57,6	79,9
	OW	1	36,8	41,9	60	28	35,4	54,4

Table 6. Examples of Handling Qualities influence for Pilot A, fore-aft approach, MTOW and sea state 5.

Simulation Test Results			DIMSS PM			ω_{cum}		
WOD (°/kt)	**SAS**	**DIPES**	**Mean**	**RMS**	**wave**	**Mean**	**RMS**	**wave**
0 / 45	Baseline	2	125,8	129	156	109,1	115	145,7
	Alternative	1	39,4	44,5	63,4	14,1	17	25,3
	OFF	3	38,4	44,5	63,8	29,9	39	56,6

Table 7. Examples of sea state influence for Pilot B, Fore-aft approach, SAS Baseline and MTOW.

Simulation Test Results			DIMSS PM			ω_{cum}		
WOD (°/kt)	**Sea state**	**DIPES**	**Mean**	**RMS**	**wave**	**Mean**	**RMS**	**wave**
0 / 60	4	3	59,5	66,3	92,6	40,6	51,1	77,3
	5	4	121,6	127,0	164,2	104,3	111,0	142,6
0 / 20	5	2	62,4	68,2	95,6	41,7	49,8	75,0
	6	3	95,3	99,6	128,0	78,2	91,4	131,6

Table 10. Metrics prediction from Pilot B control's activity model, for the following conditions:
fore-aft approach, SAS Baseline, MTOW and sea state 5.

Airwake	WOD (°/kt)	DIPES	DIMSS PM Mean				ω_{cum} Mean			
			Real	**Pred.**[(1)]	**Rel (%).**[(2)]	**Diff.**[(3)]	**Real**	**Pred.**	**Rel (%)**	**Diff**
No	10/50	3	82,1	94,6	15,2	12,5	52,3	70,7	35,2	18,4
	15/35	2	71,7	83,2	16,0	11,5	45,2	68,2	50,9	23,0
	25/40	2	99,6	104,5	4,9	4,9	64,5	97,5	51,2	33,0
Yes	0/45	2	56,5	170,0	200,9	113,5	48,2	230,0	377,2	181,8
	-10/50	4	116,0	304,0	162,1	188,0	69,3	526,0	659,0	456,7
	0/60	4	121,6	332,0	173,0	210,4	104,3	1883,0	1705,4	1778,7

[(1)] Prediction; [(2)] [(Prediction/Real)-1].100; [(3)] (Prediction-Real)

Table 11. Pilot B modified model to hover under airwake effect.

Inverse Matrix	Crossover gain (K)				Time Delay (sec)				Hysteresis (%)				Stability Gain	
	u	v	w	$\dot{\psi}$	u	v	w	$\dot{\psi}$	Ddc	Ddl	Ddm	Ddn	$K\phi$	$K\theta$
10 kt	0,2	1,0	2,5	1,2	0	0	0	0,2	1	1	1	5	-0,3	0,8

Table 12. Example of the workload metrics results for validation dataset from pilot B modified model to hover under airwake effect.

WOD (°/kt)	DIPES	DIMSS PM Mean					ω_{cum} Mean				
		Real	Pred.(1)	Rel (%).(2)	Diff.(3)	Pred.bias.(4)	Real	Pred.	Rel (%)	Diff	Pred.bias
-10/50	4	116,2	93,1	-19,9	-23,1	104,1	69,3	101,8	46,9	32,5	92,8
0/45	2	76,2	58,8	-22,8	-17,4	69,8	61,2	64,1	4,7	2,9	55,1
0/40	2	75,8	60,5	-20,2	-15,3	71,5	35,7	46,1	29,1	10,4	37,1
0/20	3	95,3	80,2	-15,8	-15,1	91,2	78,2	83,7	7,0	5,5	74,7
-15/15	3	72,1	59,6	-17,3	-12,5	70,6	51,8	58,5	12,9	6,7	49,5

(1) Prediction; (2) [(Prediction/Real)-1].100; (3) (Prediction-Real); (4) (Prediction value + training BIAS).

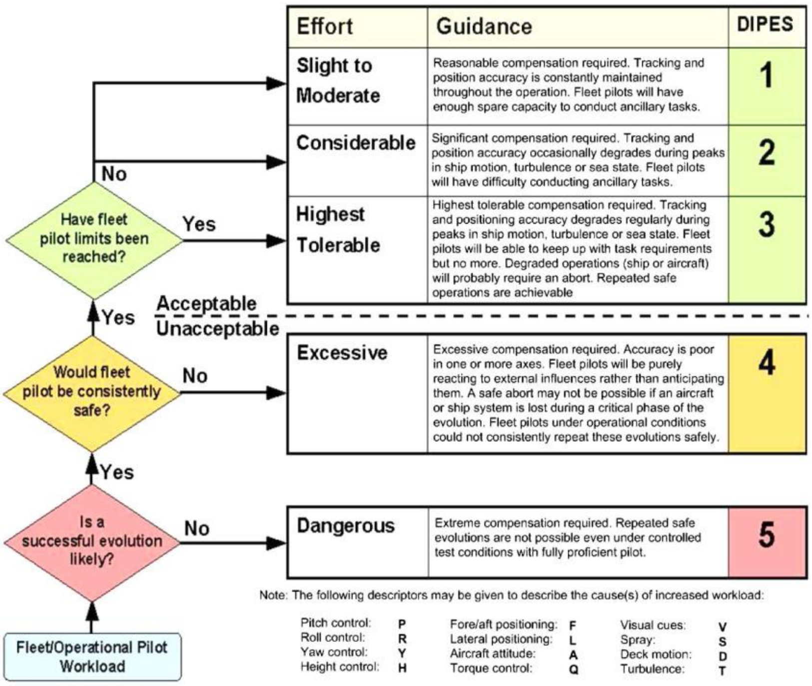

Figure 3. *Dynamic Interface Pilot Effort Scale*

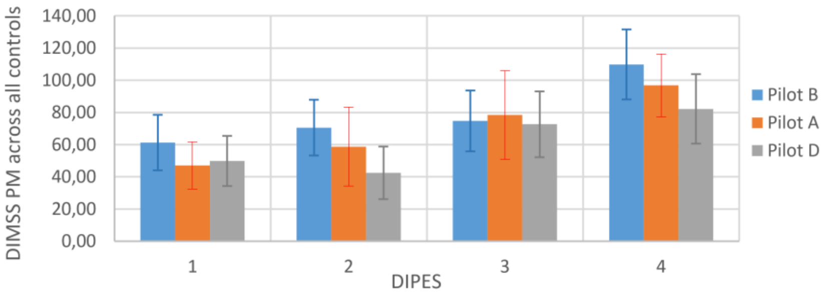

Figure 5. Average and standard deviation of the sum of DIMSS PM time history across all controls for all hovering over the deck maneuvers performed by the pilots.

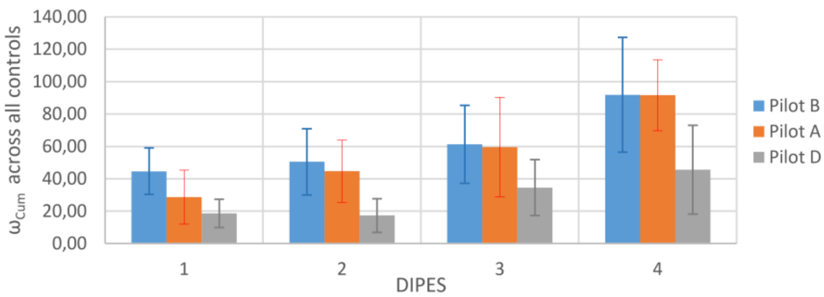

Figure 6. Average and standard deviation of the sum of cumulative power frequency time history across all controls for all hovering over the deck maneuvers performed by the pilots.

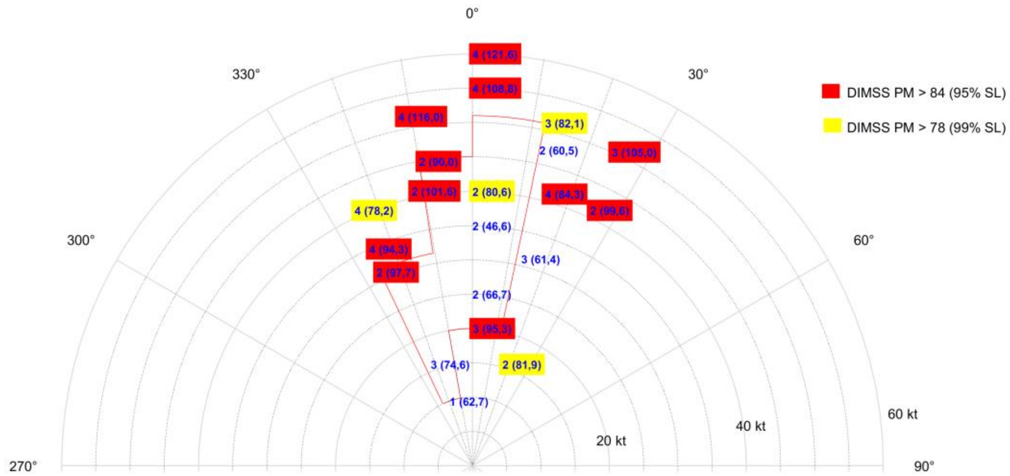

Figure 7. Comparative example between workload ratings assigned by pilot B (DIPES) and the safe workload operating limitation established based on mean of DIMSS PM (in parenthesis).

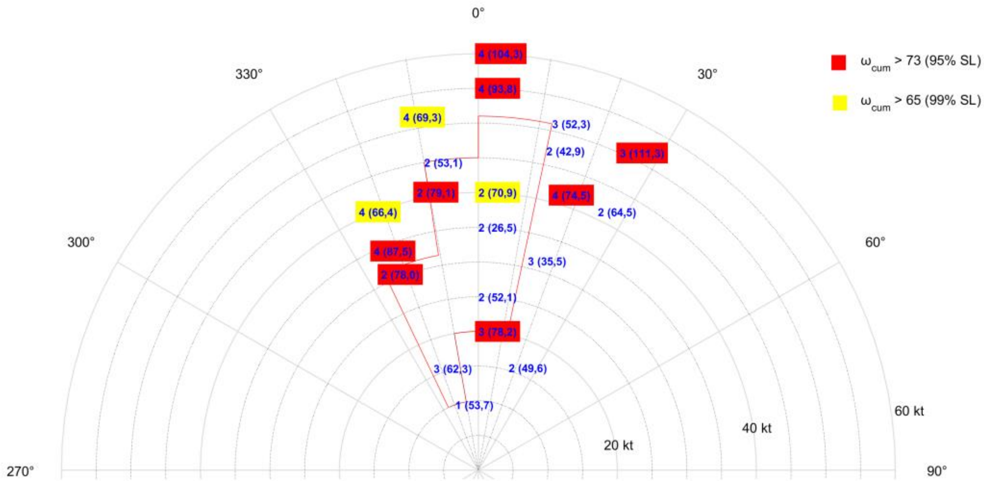

Figure 8. Comparative example between workload ratings assigned by pilot B (DIPES) and the safe workload operating limitation established based on mean of ω_{cum} (in parenthesis).

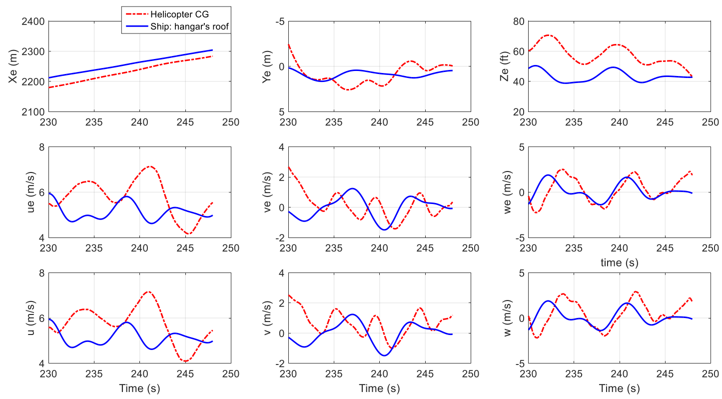

Figure 9. Example of Pilot A tracking reference for WOD of 0°/40 kt and sea state 5.

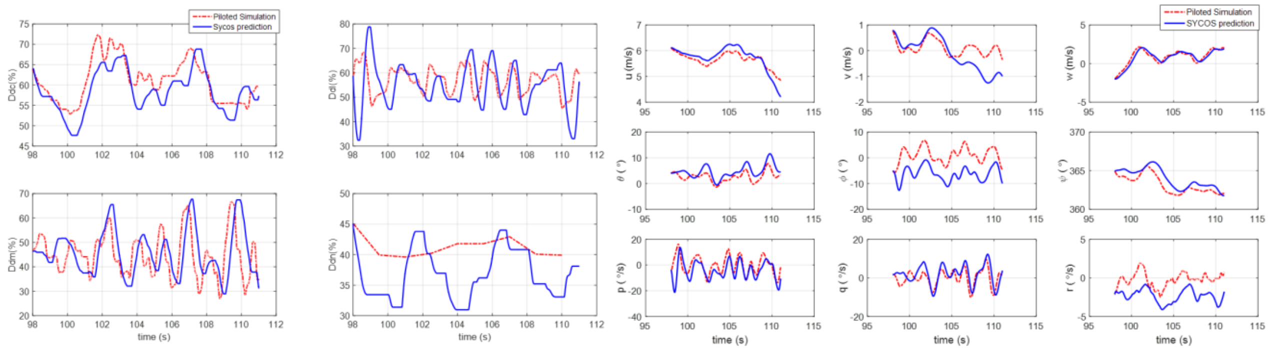

Figure 10. Example of pilot B model predictions (controls and state variables) for WOD = 15° / 35 kt (no ship' s airwake).

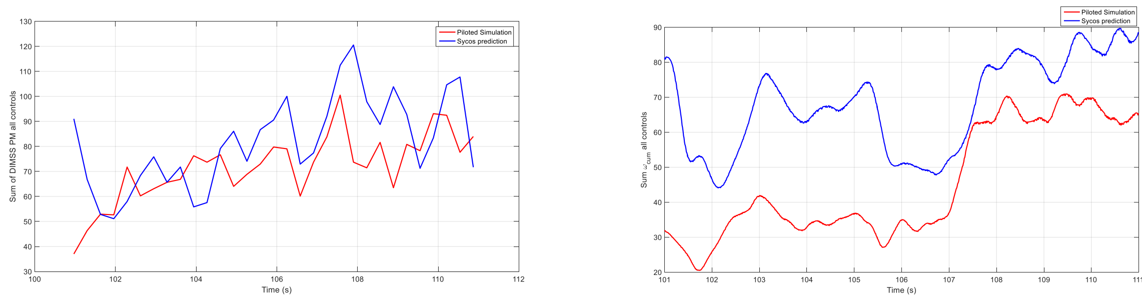

Figure 11. Example of the DIMSS PM and ω_{cum} predictions time history from pilot B model for WOD = 15° / 35 kt.

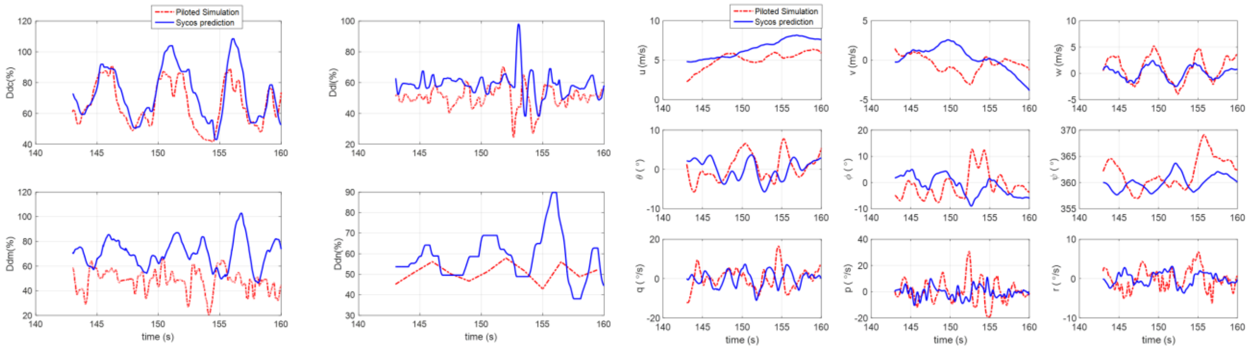

Figure 12. Example of validation dataset set predictions from pilot B modified model for hovering under airwake in WOD = -10° / 50 kt

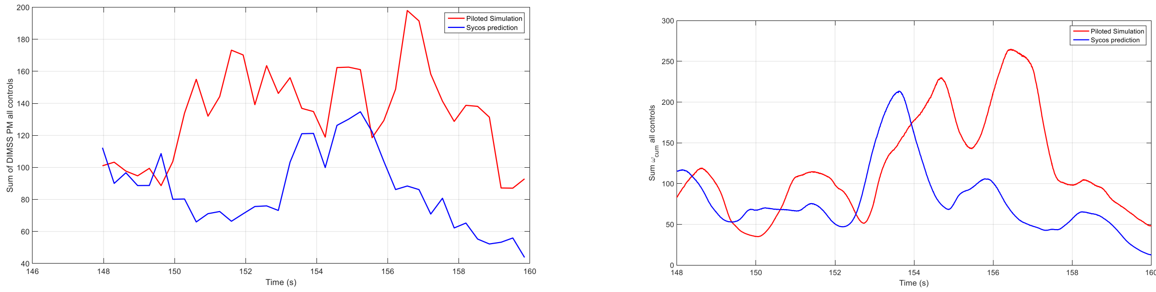

Figure 13. Example of DIMSS PM and ω_{cum} predictions time history from pilot B modified model for WOD = -10°/50 kt.