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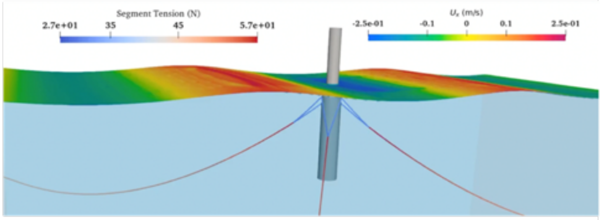

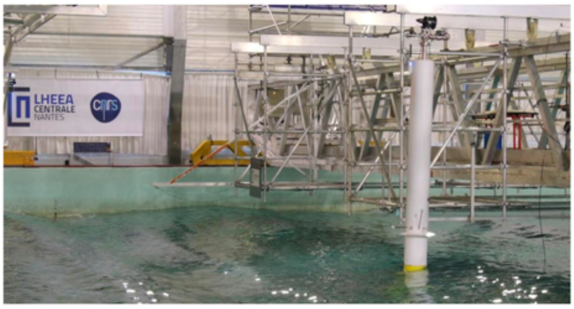

# STATISTICAL TIME DOMAIN PERFORMANCE ASSESSMENT OF BOAT LANDING TRANSFER OPERATIONS

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## Résumé

Les opérations de transfert de personnels et d'équipements, d'un navire de transport à une plateforme fixe ou flottante, dans des conditions environnementales complexes, sont des sujets délicats, de par leur nature risquée. Leur planification nécessite l'évaluation des capacités d'un navire à assurer un transfert sûr, pour des conditions environnementales données. Traditionnellement, les limites en hauteur de vagues sont utilisées pour définir l'operabilité des navires, bien que ce critère simplifie à l'extrême l'impact des vagues sur le navire [1]. Le consortium "Carbon Trust" [2] a mis au point des critères d'opérabilité, en lien avec les réponses en mouvement du navire, basés sur des essais en mer standardisés, pour aider le milieu industriel à mieux comprendre les différents facteurs limitant l'opérabilité des navires. La définition de ces critères s'appuie sur des quantités statistiques : pourcentage de glissements de la défense du navire le long du débarcadère par nombre de vagues, et moyenne quadratique de la réponse en roulis. Étant donné que la modélisation de l'opération de transfert fait intervenir des phénomènes non linéaires (adhérence/glissement), l'évaluation numérique des performances navire nécessite l'analyse statistique de simulations temporelles d'opérations de transfert. La nouvelle méthodologie présentée ici est ainsi basée sur : la représentation numérique du navire et de la plateforme en des jumeaux digitaux, suivi de la simulations d'opérations de transfert dans les conditions environnementales spécifiées, et enfin l'analyse statistique des résultats de simulations pour évaluer les capacités du navire et son opérabilité. Un cas d'application de cette méthodologie est présenté pour un couple de navire/plateforme, ainsi que les performances associées à une conditions environnementales données. Un format particulier de représentation des résultats est notamment proposé pour faciliter la compréhension des performances et aider à évaluer l'opérabilité du navire.

## Summary

Boat landing transfer operation is a sensible topic due to its inherent nature : transferring personnel and equipment from a vessel, generally a CTV (Crew Transfer Vessel), onto a fixed or floating platform, in adverse environmental conditions. Its planning requires assessing the capability of the vessel/boat landing system to ensure a safe operation, for given environmental conditions. Wave height limits are traditionally the criteria used to express vessels' operability, despite oversimplifying the impact of the waves on the vessels[1]. The Carbon Trust consortium[2] provided CTV performance acceptability criteria related to motion responses, based on a standardised sea trial program, to help the industry better understand the factors that limit CTV operations. The definition of these criteria are based on statistical quantities : percentage of fender slips per number of waves, and roll root mean square value. Since the modeling of such operation involves nonlinear phenomenons (stick/slip), the numerical evaluation of performances requires a statistical analysis on time domain simulations of the transfer operations. The new methodology presented hereafter is then based on : the numerical representation of the vessel and platform, as digital twins, followed by the simulation of transfer operations for the specified environmental conditions, and finally the statistical analysis of the simulation results to assess the performance of the vessel and its operability. The application of the methodology is presented for a CTV/platform couple, along with the statistical results of its performance in specified conditions. A particular plot format is also put forward to help assess its operability.

# I – Introduction

The installation and maintenance of facilities in the offshore wind industry rely heavily on crew transfer vessels (CTV), for the transfer of equipment and workforce. The planification of the transfer operations is then dedicated to find the best window to ensure a safe operation, at minimal cost (minimal delay for personnel and vessel). The first consideration for evaluating the capability of CTV to perform safely was historically limited to the sea state's significant wave height (usually between 1 meter, and 1.5 meters), without any real certainties on the behavior of the vessel in these conditions. In order to provide a better understanding of the CTVs' behavior and performance, preconisations were established by the Carbon Trust [2], along with the main factors limiting the transit and transfer operations. A standardised sea trial program was thus developed to assess the CTV's performance according to new criteria, based on the vessel's motions. While computer simulations are mentioned in the Carbon Trust's report, no methodology is exposed to explain how the results are obtained. The transfer operation is indeed a complex problem to model and simulate with multi-physics and multi-bodies involved. In the offshore wind industry, the operation consists in a push-on/step-across procedure, meaning that the CTV's operator pushes the CTV's fender on the boat landing, with a designed bollard pull load (usually 80% of the Maximum Continuous Rating MCR), during a relatively short period (10 minutes). The thrust is supposed to ensure that the CTV's bow remains stationary, with no slides along the boat landing, allowing a safe transfer of personnel onto the ladder. The modeling must include the hydrodynamic loads and interaction between the CTV and the platform and the contact of the CTV's fender on the boat landing, including the stick/slip and elasticity phenomena.

The publications available in the literature concerning the modeling and simulation of transfer operations focus on specific aspects. Ferreira González et al. [4] investigated the landing manoeuvre experimentally and numerically by comparing results of time domain simulations of a linear potential flow solver (with a simplified fender contact force model), with wave basins tests at model scale. While the mechanical characteristics of the fender were obtained experimentally, no boat landing was considered : the fender was directly in contact with the monopile. Despite tests being carried out in irregular waves, the evaluation of the CTV's performances, with respect to criteria, was also not part of the study. Guanche et al. [5] provided a methodology for the assessment of walk-to-work accessibility, so a different method to transfer personnel, which does not require to model the stick/slip phenomenon. The modeling was then based on a rigid, constrained multibody hydrodynamic model in frequency domain, with linearised mooring and viscous damping forces. König et al. [6] focused on a coupling strategy for the different subproblems to be solved. They proposed a partition solution strategy, based on existing software platform and solvers. More recently, Otsubo[8] and Meyer[7] studied respectively the stick/slip phenomenon and the influence of a fixed monopile on the CTV, in terms of diffraction. While these publications helped us clarify the modeling and simulation tools for transfer operations, we did not find any detailing a suitable methodology to evaluate CTVs' performances according to the Carbon Trust's criteria.

This paper is thus dedicated, not only to the modeling and simulation tools we used, but also to the methodology we developed. An anonymized application case is then presented, illustrating the results obtained with the simulation tools, but also their post-process for the evaluation of the CTV's performances, in several environmental conditions.

# II – Methodology

The main motivation of the development of this methodology was to find a way to assess a CTV's performances. Their evaluation usually goes by comparing behavior responses to thresholds, according to criteria.

## II – 1 Criteria definition

The Carbon Trust established 2 main criteria to assess the safety of the transfer operation :

- a friction or sliding criteria : 95% of waves must pass without any fender's slid above 300mm (one ladder rung)
- a roll criteria : the RMS value must not exceed 3°

We introduced an additional criteria to cope for numerical limits of our model (see section II – 2), consisting in comparing the lateral loads applying to the vessel to the bollard pull.

We also reversed the friction criteria, in order to consider the number of slips per waves, rather than the number of waves without slip.

The three criteria can thus be written :

$$\Gamma_f = \frac{N_{slips>0.3}}{N_{waves}} < 5\% \tag{1}$$

$$\Gamma_r = RMS(roll) < 3^o \tag{2}$$

$$\Gamma_l = \frac{RMS(FY_{hydro})}{BP}\% \tag{3}$$

## II – 2 Numerical modeling

The transfer operation, as performed in the offshore wind industry, relies on the push during transfer method : the vessel pushes with a designed bollard pull, usually 80% of the MCR, to ensure a minimal occurrences of fender slips on the boat landing. In order to model precisely this highly non linear stick/slip phenomenon, time domain simulations must be considered.

**FRyDoM simulation framework**

The simulations are computed using FRyDoM[3] (Flexible and Rigid Body Dynamic Modelling for Marine Operations), an open-source multi-body dynamics and multi-physics simulation framework, dedicated to complex systems modelling and simulation in a marine environment, in the time domain. Based on Project Chrono[9], an open source multi-physics simulation engine, it embeds a collision detection system and contact solver to take into account impact and frictions due to contacts between bodies.

Dedicated to marine operations and ship manoeuvring, FRyDoM embed propulsion systems, actuators and control systems. Written in full object-oriented C++ 11/14 and designed from scratch with an open API, it allows to add new features and models easily. All modules were validated against the literature, with benchmark tests and results available respectively in the open-source repository and theory documentation [15].

Hydrodynamic loads, including interactions, are modeled through the potential flow theory, with the diffraction, radiation and excitation loads coming from our in-house frequency potential flow solver, Helios[10]. Second order mean wave drift loads are computed on the vessel only, also using Helios with the far field method. Ideally, in the frequency flow solver, the vessel must be considered in its static pitch equilibrium, when pushing against the boat landing (the propulsive thrust and the boat landing reaction must be balanced by the hydrostatic pitch restoring load) in the absences of waves.

**Environment modeling**

The marine environment is considered composed of a flat seabed with finite water depth, and an irregular wave field. The wave field is modelled using linear Airy wave theory, with a directional JONSWAP wave spectrum. Directional spreading follows a $cos^{2s}$ directional law. Waves lengths are adapted to the water depth. Frequency and directional bandwidth are computed automatically, according to respectfully the peak enhancement factor and the directional spreading, so that the spreading function of the bandwidth extremas are below 0.01%.

**Mechanical modeling**

The mechanical interaction between the fender and the wind turbine transition piece (WT TP) is realised using a contact detection algorithm and a constraint solver within a non-smooth contact formulation, with neither energy restitution nor contact flexibility. The contact follows the Coulomb law for friction. Contact boxes are placed to take into account the presence of the boat landing tubes and the fender, as seen in Figure 1. The contact boxes follow the bodies in their motions.

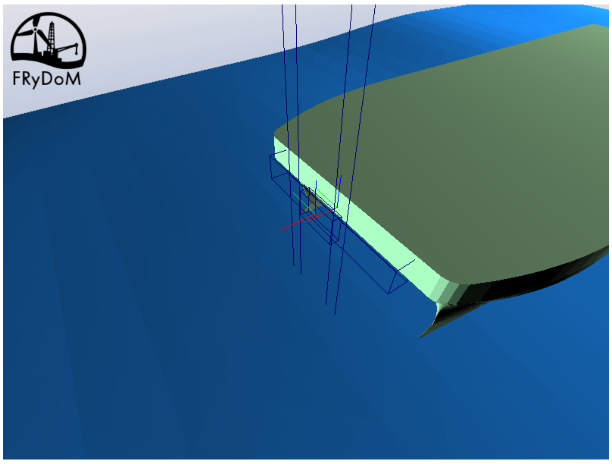


Figure 1 – Collision boxes representation, with their envelope

The wind turbine TP is modelled as a fixed rigid body. The CTV is modelled as a rigid body with 4 degrees of freedom (surge, heave, roll and pitch). Motion equations are fully nonlinear. Following the need for simulation stabilization, the sway and the yaw motions are constrained. The propulsion system is modelled with constant forces applied at the location of the vessel propellers and the total thrust is equally spread among the propellers. The direction of the thrust is aligned with the body longitudinal axis, with propellers supposed to be always immersed.

**Hydrodynamic load modeling**

Different complementary external hydrodynamic loads are applied to the CTV.

- Hydrostatics : Linear hydrostatic stiffness is applied.
- Wave excitation : Both Froude-Krylov and diffraction effects are summed. They are obtained from hydrodynamic databases generated using linear potential methods (Helios). They take into account interactions between the CTV hull and the WT TP.

- Radiation forces : The radiation forces are calculated in time-domain using the Cummins equation. Retardation functions are computed using hydrodynamic databases for first-order wave interaction. To the same extent as wave excitation forces, this model takes into account hydrodynamic interactions between the CTV and the wind turbine pile.
- Mean wave drift : The second order wave drift forces are computed using the far-field method on the CTV only, in Helios.
- Linear and quadratic extra roll and/or pitch dampings : modelling of viscous and turbulent flows effects, not modeled by the linear potential theory, and estimated from experimental or CFD roll and pitch decays.

### II – 3 Statistical analysis

The three criteria being expressed as statistical quantities, the evaluation of the performances must involve a statistical analysis of motions responses of the fender's slip on the boat landing, relatively to the waves passing, and the CTV's roll. The CTV's responses depend on operational conditions (bollard pull, loading condition, etc.) that can be considered constant during the simulations, and environmental conditions (waves). While wind and current are supposed stationary, the waves is modeled as irregular to replicate sea states. Traditionally sea states are supposed statistically converged after 3 hours of simulation. However, transfer operations are generally limited to short durations ($\approx 10\,\mathrm{min}$). Thus, we chose to simulate multiple 10 minutes operations, for the same sea state, but several sets of wave phases.

The friction, lateral and roll criteria are then statistically analysed to obtain their main characteristics : mean value, standard deviation, first and last deciles, min and max values. Since the Carbon Thrust does not mention statistical analysis, the statistical mean value is used to compare to the acceptability value given by the Carbon Thrust for each criterion. The other statistical characteristics are also shown for a more comprehensive understanding.

The statistical convergence was proven to be attained for a minimum of 400 simulations, for one sea state, with on waves mean direction, see Figure 2, using the application case presented in the following section, in its nominal conditions (bollard pull, front waves, for the specified sea state case).

## III – Application

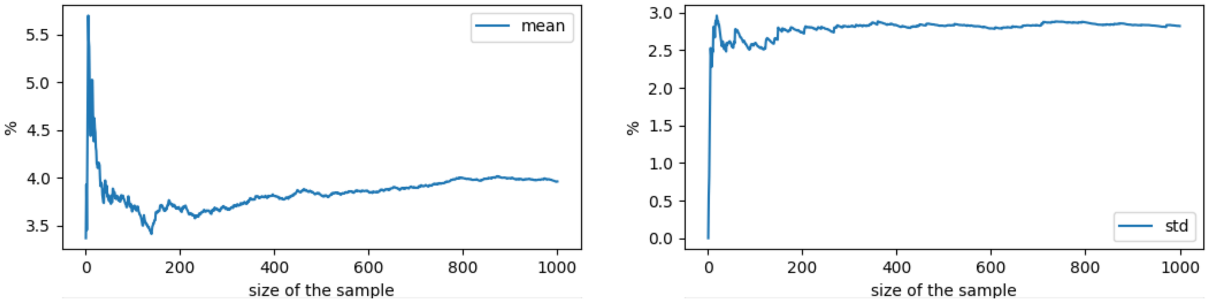
The methodology presented previously is applied to a catamaran CTV and a monopile wind turbine transition piece, on one sea state case. The setup is presented first, followed by time domain simulation results, and finally Performance Plots (P-Plots) as statistical results.

### III – 1 Application setup

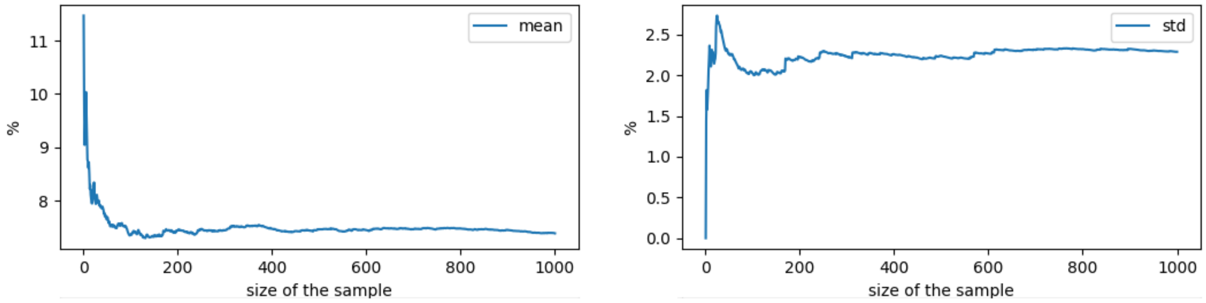
The dimensions of the catamaran CTV and the monopile are presented in Table 1 and Figure 3.

Static and dynamic friction coefficients, between the fender and the boat landing were specified as respectively 0.8 and 0.6, according to the ones measured and reported in [4].

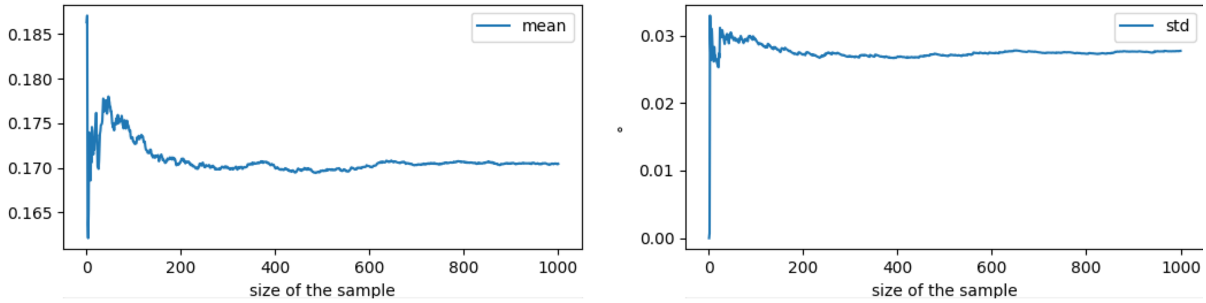
The wave excitation, radiation and wave drift force loads require the computation of their respective contributions for each wave component. These computations are per-



(a) Friction criterion



(b) Lateral criterion



(c) Roll criterion

FIGURE 2 – Statistical convergence for the different criteria (mean value (left) and standard deviation (right)).

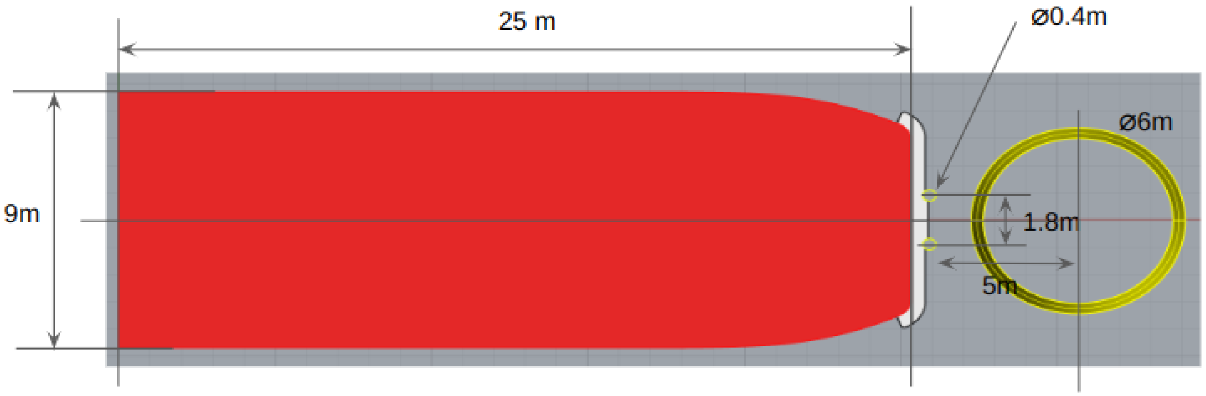


FIGURE 3 – CTV and monopile configuration plan

| | characteristics | value | symbol | units |
|---|---|---|---|---|
| CTV | length | Lpp | 25 | m |
| | breadth | B | 9 | m |
| | draft | T | 1.5 | m |
| | displacement | $\Delta$ | 100 | tons |
| | bollard pull | BP | 17.5 | tons |
| | fender width | $B_f$ | 0.6 | m |
| | inertia | $R_{xx}$ | 0.35B | tons.m$^2$ |
| | | $R_{yy}$ | 0.25L | tons.m$^2$ |
| | | $R_{zz}$ | 0.25L | tons.m$^2$ |
| | hydrostatic | $K_{33}$ | 940 | kN/m |
| | | $K_{44}$ | 10 500 | kN.m |
| | | $K_{55}$ | 32 500 | kN.m |
| | | $K_{35}$ | 700 | kN |
| WT TP | diameter | $D_P$ | 6 | m |
| | depth | H | 14 | m |

TABLE 1 – Main characteristics of the CTV and the monopile

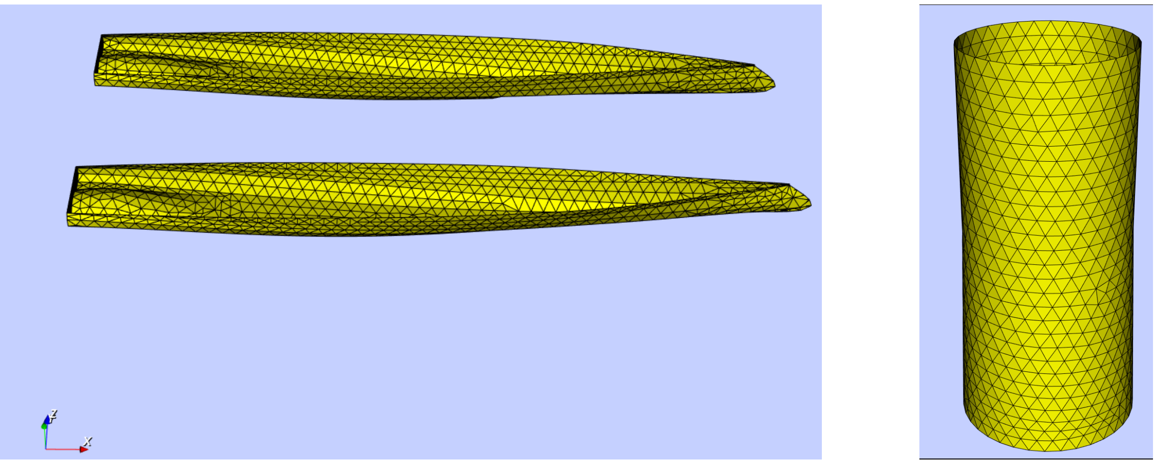


FIGURE 4 – Mesh of the wetted parts of the CTV (left) and the WT pile (right)

formed using the diffraction-radiation code Helios and the contributions are stored in hydrodynamic databases. Finally, the interaction cannot be considered for the computation of the waves drift loads, since the far-field method is used in Helios. Thus, two computations are required :

- One with the CTV only, in order to evaluate the mean wave drift loads, see Figure 4 (left) ;
- Another one with both the CTV and the WT pile for computing the added mass and damping coefficients along with the excitation loads by taking into account the hydrodynamic interactions between the two bodies, see Figure 4 (left and right).

A mesh convergence was carried out to ensure the accuracy of the different contributions. The RAOs resulting from the hydrodynamic database for the CTV only are displayed in Figure 5 in heave and Figure 6 in pitch, for different wave directions.

An additional quadratic roll damping was also considered to cope for the potential flow theory limits, with $\mu_{\phi\phi} = 1.5E6$ kg.m$^2$.

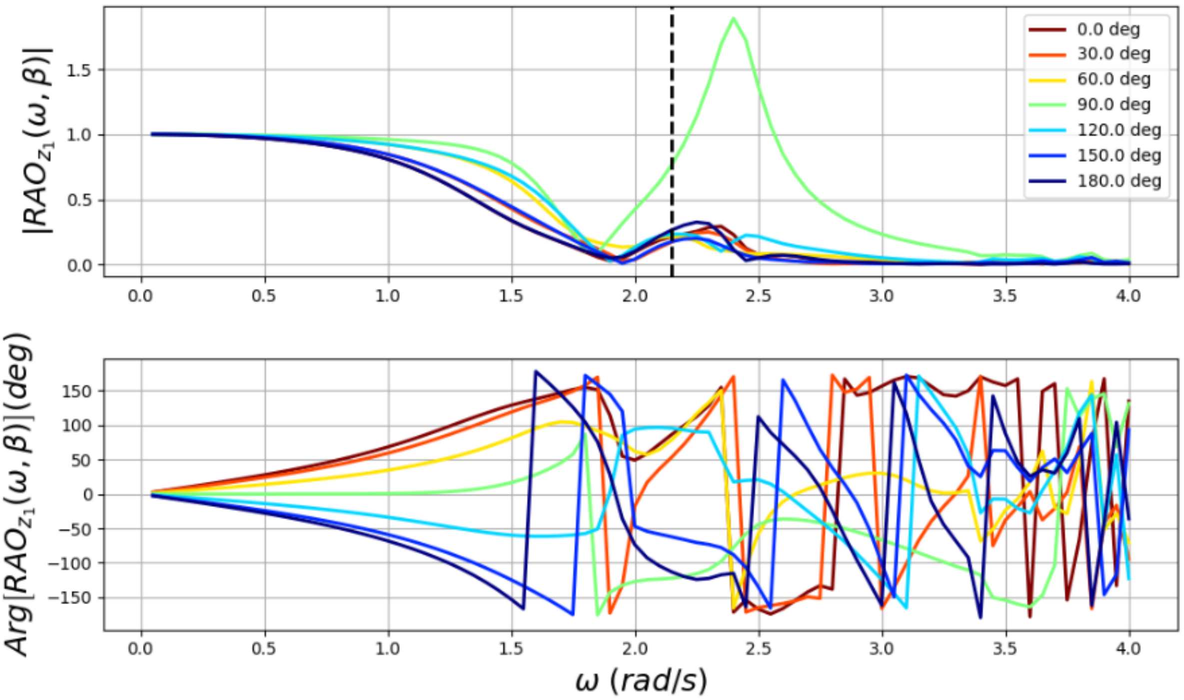


Figure 5 – Amplitude (top) and phase (bottom) of the RAO in heave of the CTV only. The vertical black dash line represents the natural frequency for this degree of freedom.

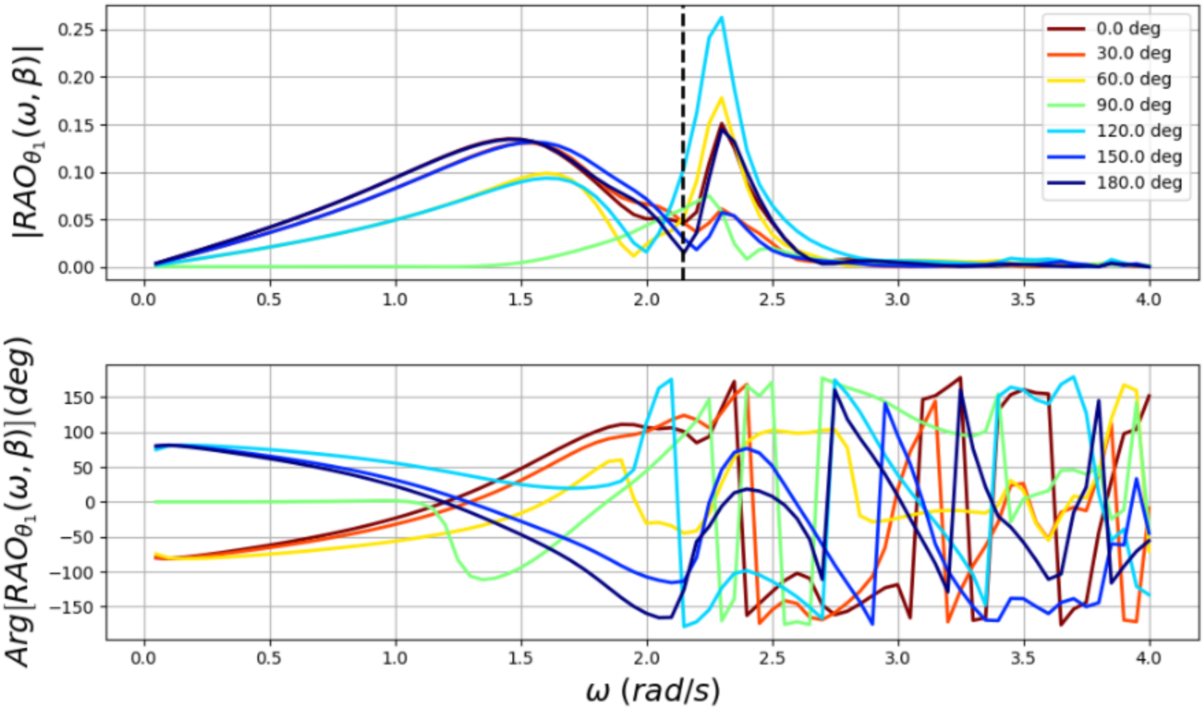


Figure 6 – Amplitude (top) and phase (bottom) of the RAO in pitch of the CTV only. The vertical black dash line represents the natural frequency for this degree of freedom.

## III − 2 Time domain results

Once all parameters are correctly setup, in FRyDoM simulation framework, time domain simulations are ran. The fender vertical position is then extracted, along with the waves elevation at the fender location.

An example of the time domain variation of both quantities is shown in Figure 7, for a sea state specified as : $H_S = 1.75m$, $T_P = 11.3s$ and $WA = 0$ degrees (front waves). The chosen set of wave phases, among the 400 simulations needed to get the statistical convergence, is particularly critical, since it yields a 11% friction criteria. Despite long stick periods (between 30 and 300 seconds, and 350 and 550 seconds), slip occurrences coincide with large wave elevations at the fender position. The fender is even not capable of sticking on the boat landing for the full last minute of simulation. As for the start of the simulation, the fender seems to stabilize at a different position than its supposed equilibrium position, but it might be due also to the large wave elevation.

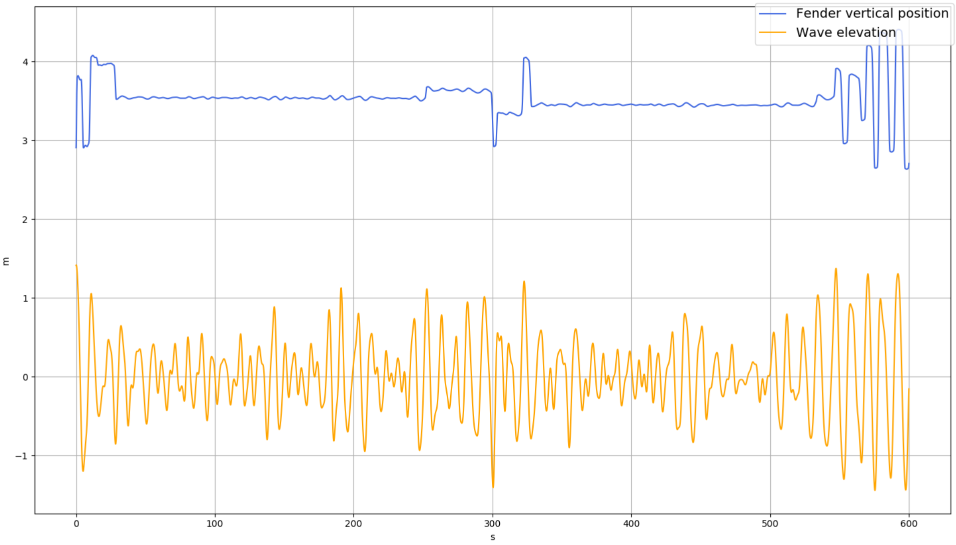


FIGURE 7 – Time domain results for the fender vertical position (blue) and wave elevation (orange) at the fender position, for the specified sea state.

## III − 3 Performances, as statistical results

The statistical CTV's responses are computed on the 400 simulations for the same sea state ($H_S = 1.75m$, $T_P = 11.3s$), for each wave direction, and the three criteria. The results are presented in Figure 8, in terms of :

- mean value : between the orange and blue domains,
- standard deviation : represented by the black segments,
- first decile : bottom of the orange domain,
- last decile : top of the blue domain,
- min and max values : represented by the extremities of the red segments.

The acceptability limits are represented by the black dashed lines, except for the roll figure, which limit exceeds the plot ranges. An arbitrary 15% limit is given for the lateral criterion, as an indication of the numerical limits inherent to the modeling. The sway and yaw DOFs are indeed numerically locked to ensure that the CTV remains in contact with

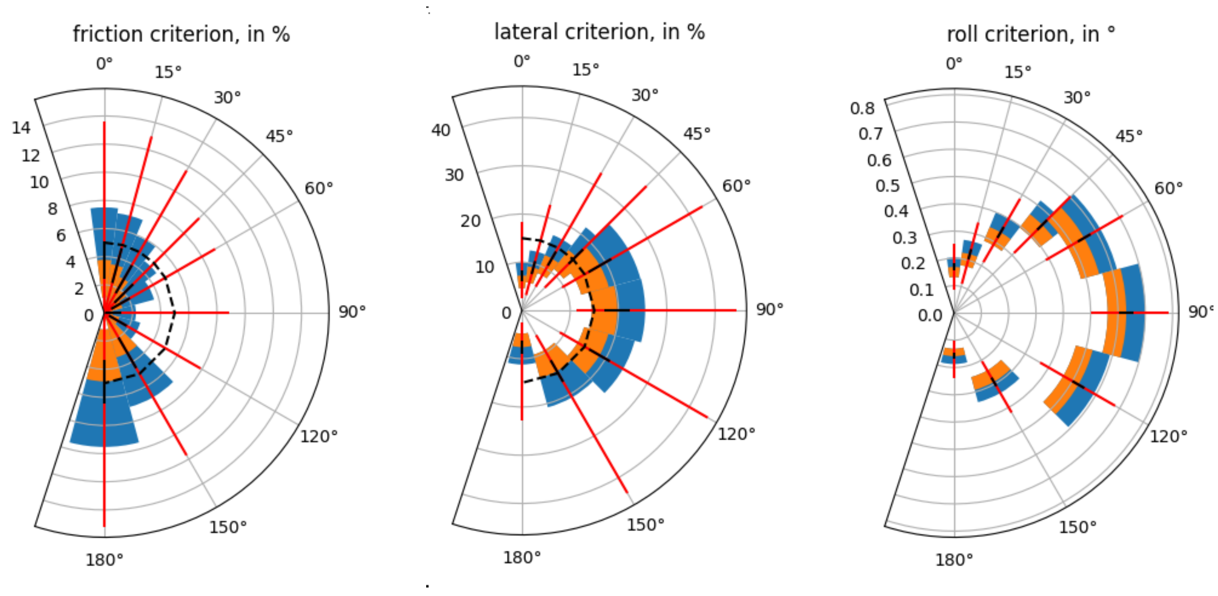


Figure 8 – of the friction (left), lateral (middle) and roll (right) criteria for a varying incident wave angle

the boat landing during the whole simulation. This may result in better performances for simulations with side waves than in regular head waves.

As can be seen in Figure 8, the friction criterion mean values are always below the acceptable limit. We can even point out that for 90% of runs, which correspond to the last decile value, the friction criterion is below 8% for head waves, but almost reaches 10% for following waves. Performances in beam waves, relatively to the friction criterion, seem better, but that may be due to the artificial numerical constraints in sway and yaw. As expected, the catamaran CTV has a very good roll response, with mean RMS values below 1 degree, mostly for beam waves. The limit for the lateral criterion is exceeded in beam waves, with mean values reaching 20%.

These P-Plots show that the CTV's operability could be extended to 1.75m Hs sea-state, for wave directions close to head waves, rather than the classical 1.5m.

## IV – Conclusions

A methodology for the evaluation of CTV's performances in boat landing transfer operations was presented. It is adapted to the offshore wind industry's procedures, in which the operation is performed according to the push-on/step-across method. The performances are evaluated according to the Carbon Trust's criteria, in friction and roll, and an additional lateral criteria, introduced for numerical reasons. Since the stick/slip phenomenon of the fender on the boat landing is capital, yielding a highly non linear multy-bodies and multi-physics problem to be solved, time-domain simulations are put forth, using the FRyDoM framework. The performances are then assessed statistically, on 400 simulations for the same operational and environmental conditions, but different sets of wave phases. The statistical quantities (mean value, standard deviation, first and last deciles, min and max values) are then computed according to each criterion definition and compared to their acceptability limits. A particular polar plot format, called P-Plots, was proposed to visualize all statistical quantities for different wave directions.

The methodology was applied to a catamaran CTV in contact with a fixed monopile wind turbine transition piece. The setup of both bodies, including hydrodynamic database and contact model parameters were presented. Performances of the CTV were shown in the P-Plots format, for one sea state condition.

Several improvements of the modeling can be suggested : the current contact handling method, based on the non-smooth Project Chrono approach is actually outdated. Fender deformation could be modeled using smooth contacts method. The propulsion is currently modeled as a constant thrust, and could be modeled more precisely and controlled along with other steering actuators to ensure that the CTV remains in contact with the boat landing. It would then be possible to get rid of the sway and yaw constraints. The lateral criterion could be changed to one more fitting to the actual operational conditions. All these computational modules (propulsion models, control strategy, etc.) are actually developed at D-ICE Engineering, and already in use within the FRyDoM framework (e.g. 3rd level Dynamic Positioning capability evaluation). Another important phenomenon which could be interesting to model is the propulsion ventilation, when the propeller exits the water, and the thrust is no longer constant.

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