Shared sea-environment definition and realisation for maritime and offshore co-simulations

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Abstract

Marine operations are often developed with the aid of numerical simulation, in particular lifting operations and transfer of cargo between different units at sea. The effect of the environmental conditions is often the limiting factor and must be included together with models of different components and sub-systems. This paper describes an approach to synchronize spatial and temporal environment information such as universal constants, current, wind, and wave for use in co-simulations of marine operations. Co-simulation models in marine operations will inherently use physical constants, wind and current velocities to calculate forces. Wind and current velocities can have spatial and temporal variations that require the models to synchronize the values. In the event of simulations in waves, the position of the ocean surface, wave particle velocities must be coherent between individual co-simulation models. This paper suggests a structured description of an environment for co-simulation of marine operations. This is illustrated through the implementation of a co-simulation of an offshore lifting operation where a vessel model, a crane, wire and payload model, as well as positioning system models are all integrated with a common environment.

Keywords: FMI, Environment, Maritime, Marine operations, Co-simulation

1 Introduction

Co-simulation of marine operations is increasingly popular both in industry and research. The co-simulation methodology enables increased fidelity through domain specific models. The FMI (Modelica Association 2014) based framework Open Simulation Platform (OSP) (OSP 2025) has introduced additions for easier configuration of marine co-simulations with pre-defined connection types implementing power bonds and control system signals. It is common for simulation models to implement a physical system situated in an environment where common physical quantities are shared and interfaced to individual models. For co-simulation of marine operations it is important that all models have an identical perception of the environment. For operations in waves the harmonic representation of the ocean surface and wave loads is of particular importance as out-of synch models will result in chaotic results where control systems, cranes, payloads and vessels have time-shifted harmonic excitation. It is also important to ensure that all models use the same constants and fluid properties when calculating the forces. Defining a common specification for how a sea environment should be represented in a marine operations co-simulation model is one of the objectives of the SEACo project(SINTEF 2021). An environment model for co-simulation of marine operations must have a mechanism for synchronization of harmonic motions between models. Another issue is the possible variations in current and wind during the simulation. Wind and currents have natural spatial and temporal variations in addition to the influence of the vessel hull and superstructure on these flow fields.

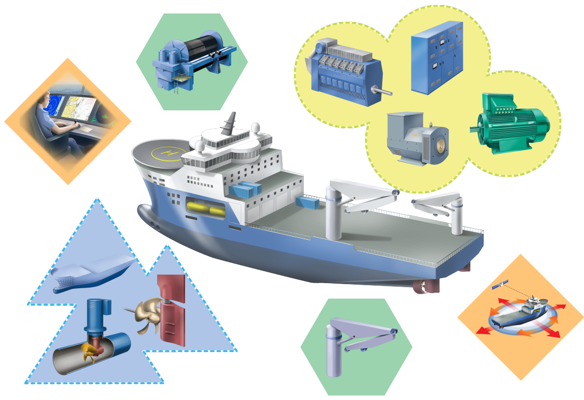

Figure 1. Systems and components important for performing safe and efficient maritime operations. Figure borrowed from the ViProMa project, (SINTEF 2025).

1.1 Marine lifting operations

Marine lifting operations are often complex and demanding, particularly when conducted from floating structures like ships. The precision of these operations is significantly influenced by environmental conditions such as wind and vessel motions. Additionally, when performing lifting operations through the splash zone and below, the lifted payload will encounter substantial environmental forces from currents, waves, and potential slamming forces upon entering the water.

To enhance operational precision, minimize environmental impact on the payload, and boost safety and efficiency, it is crucial that the entire vessel, along with all its essential systems, as depicted in Figure 1, functions seamlessly and in harmony. Therefore, the focus must shift from optimizing individual subsystems in isolation to prioritizing full-system optimization. This holistic approach is vital for improving overall performance, though it introduces significant complexity due to the intricate interdependencies between various subsystems, especially as the trend towards increased autonomy in demanding marine operations continues.

To illustrate, the *Dynamic Positioning* (DP) system must maintain the vessel's position and desired orientation with precision, while the crane operates, largely independent of the DP system, to control the payload's motion. Both the crane and DP systems draw power from the vessel's power system and are significantly affected by stochastic environmental conditions, which also impose requirements on onboard power production. This example merely scratches the surface of the complexity involved in such operations.

Minimizing the risk of operational failure, which can manifest as exceeding safety limitations or damaging the payload, is crucial. This risk can be mitigated through various methods, such as crew training, advanced onboard decision support systems (Skjong, Lars T Kyllingstad, et al. 2019; Lars Tandle Kyllingstad et al. 2023), and virtual prototyping of the operation itself (Skjong and Pedersen 2017a). The latter involves testing different operational strategies in simulators, as demonstrated in this work. Additionally, onboard decision support systems can be either data-based, physics-based, or a combination[1].

1.2 Sea environment

The important environmental conditions for marine operations are wind and current together with waves. Current is commonly represented in simulation models as vector fields with spatial variation. The temporal variation is often neglected since the time scales of changing ocean currents are usually larger than the duration of lifting operations. The temporal variations of wind cannot be neglected. Wind is described by a mean wind speed and direction, but with added gust variations in both speed and direction. Gusting describes flow phenomena that has a statistical description in the form of spectrums. Depending on the direction, the wind may be disturbed by the superstructure, creating a wake.

The surface waves that comprise a sea-state is a complex phenomena that is described by wave spectrums. Wave spectrums define the distribution of energy between different wave frequencies in a specific sea state. The distribution can be derived from oceanographic modelling, measured experimentally or from standardized wave spectra parametrized by simpler statistics such as significant wave height and peak period. For long crested seas all waves share the same direction whereas short crested seas make use of a directional spectrum to distribute wave energy among wave directions. In this paper we assume JONSWAP (K. Hasselmann et al. 1973) distributed wave energy and a simple $\cos^2$ directional distribution around a mean direction. A wave spectrum is a model of how energy is distributed between different wave frequencies in the frequency domain, while most simulation frameworks are developed for the time-domain. Wave spectrums can be converted to the time-domain by sampling the spectrum in the frequency domain and lumping the energy from the continuous spectrum into a finite set of harmonic functions. Figure 2 illustrate the process of converting a wave spectrum into a time-domain wave. To avoid an unreasonably large response at the origin, each component in the realisation must be phase shifted by a random value.

[1] A combination of data- and physics-based is preferable over pure data-based methods due to the reduced need for extensive training data required.

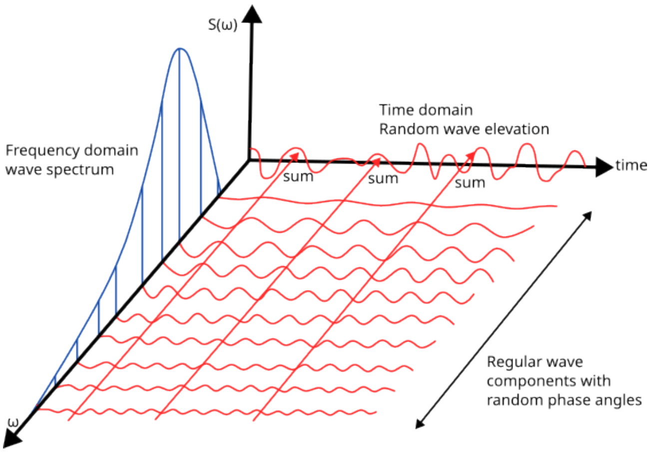

Figure 2. Relationship between frequency domain wave spectrum and time domain realisation by Fourier series. Adapted from (Faltinsen 1993)

Wind and waves are realised in the time domain in a fashion similar to Fourier series where frequencies and amplitudes are selected to replicate the energy distribution of the underlying power spectra. A shared environment model for marine lifting operations must represent:

- Ocean current magnitude and direction with possible spatial variation
- Wind speed and direction with gust variations, spatial variation and possible shielding effects
- Frequency and directional distribution of wave energy

In a co-simulation setting this information must be synchronized across all participating models. Particular attention has to be paid to the Fourier-series.

1.3 Previous work

Common parameters and calculations are easily implemented in monolithic simulation environments. Envi-

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ronments based on the Modelica language enables sharing of common resources with the inner/outer instances of generic classes. An example of a purpose built tool for marine operations is FhSim (Reite et al. 2014; Su et al. 2019) that implements numeric integration of ODE models, where the environment information and calculations are centralized in an environment model that is directly accessible by memory location as a global resource. A global singleton object is a common solution when all of the connected models are in a single process. Simulation models that are distributed and communicate across narrowly defined interfaces are nevertheless an attractive proposition in the marine industry where multiple models, and sometimes physical equipment, must be integrated in simulators for training, operation design and integration tests. Training simulators are a particular case where heterogenous software and equipment are combined to place a human operator in an immersive simulation environment operating in real-time. High-Level-Architecture (Dahmann, Fujimoto, and Weatherly 1997) has seen widespread adoption for integrating heterogenous models into a common simulator, particularly for training simulators. (McTaggart et al. 2021) shows the development of an HLA based simulator for ship-to-ship replenishment at sea. The simulator case is similar to offshore crane operations in the sense that it consists of a sea environment, a vessel, an external load, and interaction effects. The interaction effects are dissimilar in that instead of propulsors interacting with themselves, the environment and hull. The simulator in (McTaggart et al. 2021) consists of two ship federates, a replenishment equipment federate, a seaway federate and a hydrodynamic interaction federate to capture interaction effects between the two ship federates. HLA relies on common software libraries that communicate over an Run-Time-Infrastructure (RTI), and even if the HLA standard facilitates re-use by the definition of Federate Object Models, simulators must use a common RTI software to manage execution and exchange data. This is different from the FMI standard that describe co-simulation with a minimal interface between models where the same binary code can be used in different simulation environments.

There has been demonstrations of FMI based co-simulator frameworks for marine operations such as (Z. Liu et al. 2023), where a FMI based co-simulation software was used to simulate vessel motions and an attached crane. The environment in model in (Z. Liu et al. 2023) is described as affecting the vessel motions but not the crane. The crane lifting wire, slings, and payload is absent from the simulation and is therefore not connected to the environment definition. The environment model in (Z. Liu et al. 2023) describe the sea state as a collection of Fourier components.

2 The SEACo environment

A sea environment description for FMI-based co-simulation must represent quantities ranging from simple constants to power spectra. The purpose of placing the environment in a single model is to reduce errors by providing a common source of values. A single data source can provide wind, current, and waves from both conventional constant values, from pre-calculated datasets, and time-domain realisation of power spectrums on standard forms. The models in a co-simulation of marine operations will often calculate environmental forces by either assuming slender structures and applying the Morrison's equation (Eq. 1), and/or apply linear wave theory with superposition of forces generated by individual waves as described by Eq. 3.

Eq. 1 is applied to rigid bodies where the submerged volume V , drag coefficient C_d, added mass coefficient C_a are intrinsic to the shape and the fluid density ρ, the relative velocity v and relative acceleration $\dot{v}$ are properties of the environment.

$$F = \frac{1}{2}\rho A C_d v^2 + C_a \rho V \dot{v} \tag{1}$$

Fluid density, acceleration and velocity will have temporal and spatial variation in marine simulation models, i.e., when currents vary in magnitude and direction through the water column, or varying density from patches of brackish water. A shared environment model needs to provide both physical constants and fluid velocity information as a function of time and place.

Linear wave theory can represent a wave spectrum by a sum of sin-functions. models can calculate the surface elevation by evaluating Eq. 2

$$\zeta(x,y,t) = \sum_{i=0}^{N} \zeta_{a,i} \sin(\omega_i t - k_{x,i} x - k_{y,i} y - \varepsilon_i) \tag{2}$$

where $\zeta_{a,i}$,ω_i,$k_{x,i}$,$k_{y,i}$ and ε_i is the individual wave height, wave frequency, wave numbers in x and y direction and random phase angle respectively from the spectrum realisation. The choice of $\zeta_{a,i}$, $k_{x,i}$ and $k_{y,i}$ and ω_i for individual waves depends on the two spectra for the energy distribution between frequencies and the energy distribution in the wave direction. The method of converting the frequency domain wave spectrum into Fourier components and allocating the individual waves to a direction depend on the choice of number of Fourier components, random number generation and implementation of the spectra distribution functions.

A representation of the wave surface with superposition of pre-calculated amplitudes precludes the use of higher order methods to describe waves. However, the linear superposition of waves allows models to compute the instantaneous surface position. The dynamic pressure, wave particle velocity and accelerations can be derived from the individual wave velocity potentials as seen in Equation 3.

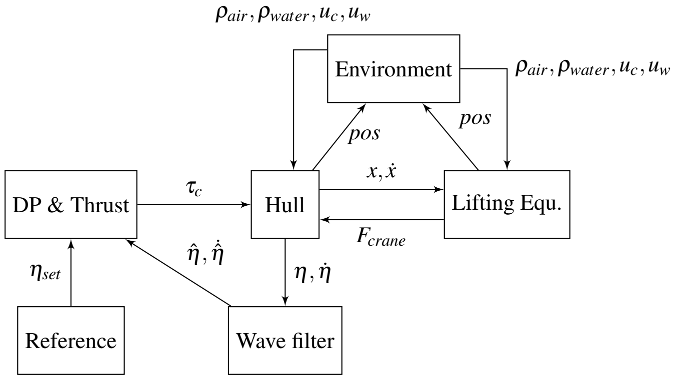

Figure 3. Co-simulation setup of vessel in a dynamic positioning operation with lifting equipment.

This makes it possible to model wave forces on slender structures such as crane wires and payloads in marine lifting operations.

$$\Phi_i(x,y,z,t) = \frac{\zeta_{a,i}g}{\omega_i}e^{-kz}\sin(\omega_i t - k_{x,i}x - k_{y,i}y - \varepsilon_i) \quad (3)$$

Eq. 3 contains the same variables as Eq. 2 and the combination of the equations can be used for calculating forces on slender structures and ventilation of propellers. Linear wave theory is also used in sea-keeping calculations that derive hydrodynamic forces as a function of wave frequency, direction and amplitude. See (Faltinsen 1993) for common applications of linear wave theory in offshore applications.

This paper propose dividing the specification sea-environment for co-simulation of marine operations into levels as seen in Table 1. Not all models need information about the waves, nor spatial and temporal variation of current and wind. The levels of specification makes it possible to classify a simulation model as supporting synchronized environments on different levels. Global current and wind can be discerned from spatial current and wind by checking model connections for a coupling of position information between the model and the environment with the origin as a default value for input port values.

Specification level 0 would make the constants required in Eqs. 1-3 available from a common source. The level of the environment description that is shared is increasingly sophisticated and the last level would include interaction between models through the environment for instance loss effects on propulsors from interaction effects between propeller jets, hull and surface.

3 Methods and Materials

3.1 Models and simulation setup

Figure 3 illustrates the co-simulation setup for the case study presented in this work. The subdivision into FMUs represent different disciplines that cooperate to establish a model of a marine operation. Control systems (DP-controller, wave-filter, thrust-allocation), Hydrodynamics (hull, propulsors), Mission specific equipment interconnected with the common Environment. Other subdivisions are possible, but the separation into FMUs reproduce real-world system boundaries where signals are sampled in control systems. ρ_{water}, represents the water density, and ρ_{air}, the air density. The vector u_c holds the water current speeds, which can be depth-dependent, and u_w holds the wind speed. τ_c is the thrust force vector in the vessel's body reference frame calculated by the DP control system. The yaw angle of the vessel is represented by ψ. The position and velocity vectors for vessel being fed to the lifting equipment model are x and $\dot{x}$, respectively. F_{crane} is the force feedback from the lifting equipment model. The desired position and orientation of the vessel are given by η_{set}, while $\hat{\eta}$ and $\dot{\hat{\eta}}$ represent the filtered position and orientation of the vessel, along with their corresponding rates. Finally, η and $\dot{\eta}$ denote the position and orientation of the vessel, and their corresponding rates. Note that information provided by the environment about the surface elevation (due to waves) are omitted in the figure. It is out of scope here to describe each model shown in the figure in detail, but a brief overview will be provided in the following.

3.1.1 Environment

A simplified environmental description was implemented that supported specification levels 1-3 from Table 1. The sharing of information is implemented with the port system and the environment output include acceleration of gravity (g) and the densities for air and water (ρ_{air} and ρ_{water}, respectively). The output of wind and current magnitude and direction is implemented with a vector input for positions with a corresponding output with velocity magnitude of wind and current. The first three values in the position input correspond to the directional components of the wind and current in the first three output values. Here, the wind is assumed constant while the current profile follows an exponential decay with increasing depth:

$$v(z)_{curr} = v(z=0)_{curr}e^{-az} \quad (4)$$

The wind, current and decay rate values are set as parameters. The waves are generated from a JONSWAP spectrum for a given significant wave height (Hs) and peak period (Tp) pair, and the mean wave direction. Here, the number of Fourier components are set to 24 and the spectrum is realised by random sampling of the wave frequency in the interval $(0, 2\pi]$. The wave direction is randomly selected from a cos^2 distribution centred on the mean wave direction. The wave directions are assigned to the individual waves by descending wave amplitude and distance from the mean wave direction. Wave phase angles was randomly selected. Each wave require four values, as shown in Eq. 2, to be specified resulting in 4 vector ports or 96 individual ports to be connected to the other models. The values on the output ports of the simplified environment model are constants. But usage of the port

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Table 1. Specification levels for synchronized environment.

Level of Specification	*Description*	*Example*
0	Basic constants	Identical constants are used from a common source. Can be achieved with constant value signals.
1	Global current and wind	Global wind and current values as input coupled to a common source. Can be achieved with constant value signals.
2	Spatial current and wind	Wind and current based on individual positions. To model spatial and temporal variations in current and wind around the vessel and in the water column. Requires input of position where wind and current is observed, eg. payload position as input results in output of current and wind velocities at payload position. Centralized implementation of wind gust spectrum.
3	Synchronized wave definition	Centralized implementation of wave energy and direction spectrum formulas and realisation of individual waves. Output list of wave components allows connected models to calculate surface elevation, wave particle motions and utilize sea-keeping results from linear wave theory.
4	Propulsor interaction	Propulsor losses can be introduced by phenomena such as the Coanda effect, inflow disturbance and propeller jet interaction. There are no general methods for including such effects in a flexible reconfigurable environment such as co-simulations.

system ensures that changes in environment values will be reflected in the interconnected models.

3.1.2 Hull

The hull geometry is analysed using *HAMS*, an open-source computer programme for the analysis of wave diffraction and radiation of three-dimensional floating or submerged structures (Y. Liu 2019). The hydrodynamic results from the analysis are transformed into a state-space time-domain formulation as presented in (Thor I. Fossen 2005). The equation of motion for the hull is given in Eq. 5.

$$\dot{\eta} = \mathbf{J}(\Theta)\nu \tag{5a}$$

$$\mathbf{M}\dot{\nu} + \mathbf{C}_{RB}\nu + \mathbf{D}\nu + \mu + \mathbf{g}(\eta) = \tau_{env} + \tau \tag{5b}$$

In (5) the vector η represents the generalized position and orientation of the vessel given in the NED-, *North, East, Down*, reference frame. The matrix $\mathbf{J}(\Theta)$ is the transformation matrix dependent on the Euler angles Θ, which describe the vessel's orientation. The vector ν represents the generalized velocity of the vessel, including both linear and angular velocities. The matrix $\mathbf{M}$ is the generalized mass matrix, which includes both the rigid-body mass and the added mass due to hydrodynamic effects. The matrix $\mathbf{C}_{RB}$ represents the Coriolis and centripetal forces due to the rigid-body motion of the vessel. The matrix $\mathbf{D}$ is the linear damping matrix, which accounts for the hydrodynamic damping forces acting on the vessel. The vector μ represents the memory effect of the fluid, which is modelled as an integral term involving the retardation function. Note that μ can be approximated by a linear reduced-order state-space model, as described in (Perez and Thor I. Fossen 2011). The vector $\mathbf{g}(\eta)$ represents the restoring forces and moments due to gravity and buoyancy, which depend on the position and orientation of the vessel. The vector τ_{env} represents the environmental forces acting on the vessel, including wave, wind, and current forces. The vector τ represents the control input forces and moments applied to the vessel.

The hull model outputs position, orientation, and corresponding rates for its centre of gravity, as well as for fixed positions on the hull. It takes forces as input, both described in the NED reference frame and in the body-fixed reference frame. The hull also gets environmental information from the environmental model, such as information about the water density (ρ_{water}), the wave components (direction, amplitude, frequency, phase, etc.), and the wind conditions (speed and direction).

3.1.3 Lifting Equipment

This lifting equipment model consists of a crane-tip, a wire model, four slings and a rectangular payload, and the model is developed based on the framework presented in (Skjong, Reite, and Aarsæther 2021), which focuses on lumped, constrained cable modelling using an explicit state-space formulation. This model simulates the dynamics of a payload being lifted by a crane-wire, accounting for various forces acting on the system, including wind forces, buoyancy, first-order wave forces, and drag forces. The drag force is calculated with Eq. 1 and the first-order wave force is calculated by assuming a fully submerged payload and using Eq. 3 to calculate the wave force from each wave component as

$$F_j = \sum_{i=0}^{N} \rho_{water} V \frac{\delta^2 \Phi_i}{\delta j \delta t} \quad \text{for j=x,y,z} \tag{6}$$

Where V is the payload volume and Φ is given in Eq. 3.

The model employs a lumped parameter approach, where structural elements are represented by discrete mass nodes connected by constraints. These constraints are solved explicitly using an elastic version of Baumgarte stabilization (Baumgarte 1972), ensuring numerical stability and avoiding singularities in matrix inversions. The Baumgarte stabilization method reformulates constraint forces to handle differential-algebraic equations, allowing efficient numerical integration. The model receives the vessel position, orientation and corresponding rates and offset from the center of gravity as inputs and calculates a force vector that is applied to the vessel in the centre of gravity through a port coupling.

3.1.4 DP, thrust and references

The DP controller is here assumed to be a simple PID-controller that controls the global thrust force vector needed to keep the vessel in position, as presented in (Skjong and Pedersen 2017a). The equations in the DP-controller are given as

$$\tau_c = (\mathbf{R}_z(\psi))^\top \left[\mathbf{K}_P \mathbf{e}_P + \mathbf{K}_D \dot{\mathbf{e}}_P + \mathbf{K}_I \int_0^t \mathbf{e}_P \, dt \right] \tag{7}$$

In the equation the control force vector is denoted by τ_c. The rotation matrix $\mathbf{R}_z(\psi)$ is a function of the yaw angle ψ, which describes the vessel's orientation about the vertical axis. The transpose of this rotation matrix is $(\mathbf{R}_z(\psi))^\top$. The proportional gain matrix is $\mathbf{K}_P$, and the error in the position vector is $\mathbf{e}_P$. The error is defined as the difference between the desired position and orientation of the vessel, and the measured (filtered measurements) position and orientation of the vessel. Note that the desired position and orientation of the vessel could be fixed scalars or slowly varying variables, and are modelled in the *Reference* model shown in Figure 3. The derivative of the error in the position vector is $\dot{\mathbf{e}}_P$, and the derivative gain matrix is $\mathbf{K}_D$. The integral of the error in the position vector over time is $\int_0^t \mathbf{e}_P dt$, and the integral gain matrix is $\mathbf{K}_I$.

In this co-simulation study, propulsors and thrust allocation are omitted. The global thrust command vector from the DP controller is acting directly as the thrust force on the hull. This can be argued for since the main focus is the lifting equipment and the payload being lowered into the sea with a common envionment. For a well designed thrust allocation algorithm and well-tuned control system, the dynamics of the complete propulsion system should be comparable to the output of the DP-controller.

3.1.5 Wave filter

The wave filter is used to filter out first order motion oscillations for the vessel, which in general, is not needed to compensate for, nor possible in realistic operations without spending an enormous amount of energy. Hence, the wave filter provides the dynamic positioning system with the filtered vessel position, orientation, and corresponding rates. The filter is of a passive non-linear observer design, as elaborated in (Thor I Fossen and Strand 1999), and its dynamics are described by the equations listed in (8).

$$\dot{\xi} = \Omega \xi + \mathbf{K}_1 \bar{\mathbf{y}} \tag{8a}$$

$$\dot{\eta} = \mathbf{J}(\mathbf{y}) \hat{\mathbf{v}} + \mathbf{K}_2 \bar{\mathbf{y}} \tag{8b}$$

$$\dot{\mathbf{b}} = -\mathbf{T}^{-1} \mathbf{b} + \frac{1}{\gamma} \Lambda \bar{\mathbf{y}} \tag{8c}$$

$$\mathbf{M} \hat{\mathbf{v}} = -\mathbf{D} \hat{\mathbf{v}} + \mathbf{J}^T(\mathbf{y}) \dot{\mathbf{b}} + \tau + \frac{1}{\gamma} \mathbf{J}^T(\mathbf{y}) \mathbf{K}_3 \bar{\mathbf{y}} \tag{8d}$$

$$\hat{\mathbf{y}} = \hat{\eta} + \Gamma \xi \tag{8e}$$

In the filter, the state vector ξ represents the wave-induced motion. The matrix Ω describes the dynamics of this motion, while $\mathbf{K}_1$ is the observer gain matrix for the wave-induced motion. The estimation error vector is denoted by $\bar{\mathbf{y}}$. The position and orientation vector of the vessel is η, and $\mathbf{J}(\mathbf{y})$ is the transformation matrix dependent on the vessel's position and orientation. The estimated velocity vector of the vessel is $\hat{\mathbf{v}}$, with $\mathbf{K}_2$ being the observer gain matrix for the position and orientation. The bias vector $\mathbf{b}$ accounts for slowly varying environmental disturbances. $\mathbf{T}^{-1}$ is the inverse of the diagonal matrix of bias time constants, and γ is a scalar tuning parameter. The matrix Λ scales the amplitude of the estimation error. The mass matrix of the vessel is $\mathbf{M}$, and $\mathbf{D}$ is the damping matrix. The transpose of the transformation matrix $\mathbf{J}(\mathbf{y})$ is $\mathbf{J}^T(\mathbf{y})$. The control input vector is τ, and $\mathbf{K}_3$ is the observer gain matrix for the velocity estimation. Finally, $\hat{\mathbf{y}}$ is the estimated measurement vector, and Γ is the matrix representing the relationship between the wave-induced motion and the measurements.

This filter gets the vessel position and orientation as inputs, and is tuned with knowledge about the wave conditions and the vessel dynamics. The output of the filter is the filtered vessel position and orientation, along with corresponding rates. Figure 4 shows illustrates the performance of the wave filter, where the vessel's first order motions in the north position has been filtered.

3.2 Co-simulation setup

The Open Simulation Platform programme `cosim` (OSP 2025) was used to run simulations. cosim includes a `VariableGroup` mechanism to ease interconnection of models with a large number of ports, and the wave component parameters were combined into `VariableGroups` for ease of use. Main parameters used in the co-simulation is shown in Table 2

Simulations were run on a Intel I9-12900 with 64GB RAM and the simulation consumed 1006[s] CPU time for 1200 [s] simulation time (790[s] wall-clock time due to parallel execution).

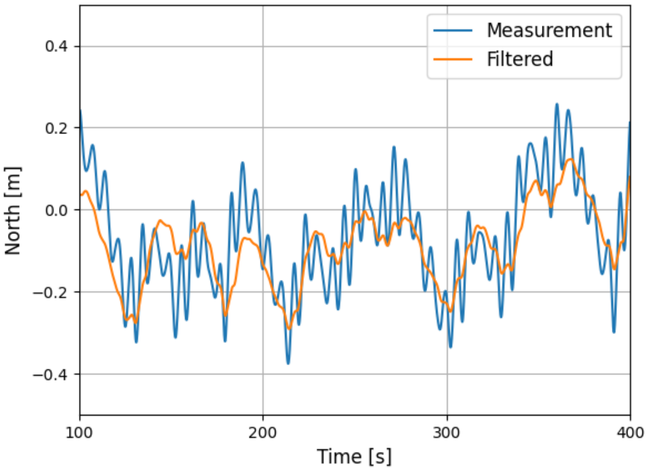

Figure 4. Wave filter performance example where the vessel's first order motions in the north position has been filtered.

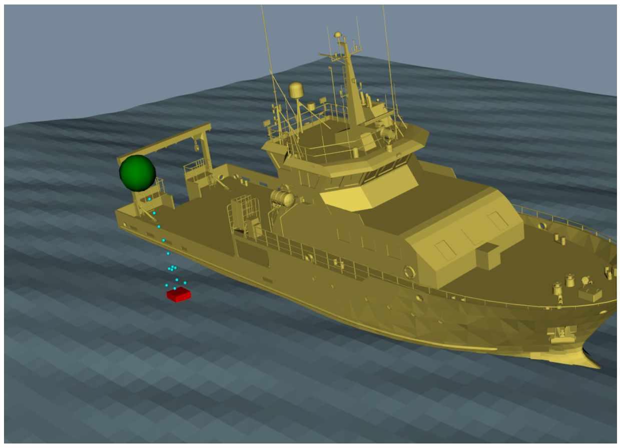

Figure 5. VTK visualization of the position traces in Figure 6. The image shows values derived from the environment model, ship model, crane point with wire and load. Red colour on load signifies water contact

Table 2. Main parameters in co-simulation.

Parameter	*Value*
Ship size	$36.25[m]$ x $9.6[m]$ x $2.7[m]$
Ship mass	$574\ [tons]$
Crane height	$8\ [m]$
Crane boom length	$5\ [m]$
Crane base offset	$5.5\ [m], -4.5\ [m], 1.15\ [m]$
Payload size	$1[m]$ x $1[m]$ x $1[m]$
Payload mass	$5\ [tons]$
Wire diameter	$0.03\ [m]$
Winch speed	$0.05\ [m/s]$

4 Results

The system model shown in Figure 3 was defined in `cosim` with separate FMUs for each box in the figure. The communication stepsize was $0.01[s]$ and results from the individual FMUs were saved in separate csv files. A VTK based visualization was developed that animated the visual components from the different FMUs in 3D based on the contents of the individual csv files. The results of a hull with attached crane & payload in a irregular wave field is shown in Figure 5. The parameters of the individual waves in Figure 5 is transmitted to both vessel an crane & payload model. The resulting position trace for the hull, crane tip and payload from a $120[s]$ simulation with the payload in the wave zone for $Hs = 1[m]$ and $Tp = 7[s]$ is shown in Figure 6. The position trace shown the harmonic oscillations of the vessel in linear and angular degrees-of-freedom and amplified by the lever arm at the crane-tip, the figure also shows the resulting motions of the payload at the end of the crane wire. The payload will experience wave forces in the wave zone together with buoyancy and The tension in the crane wire and the magnitude of the buoyancy and first-order wave force on the payload are shown in Figure 7. The buoyancy and wave forces are only activated when the payload is in contact with the ocean surface as shown in the bottom panel of Figure 7. Note that this model does not include slamming loads that is a limiting phenomenon in offshore lifting operations.

Two $1200[s]$ cases were simulated to allow the payload to transition through the wave zone and through the water column. The simulation time also test the wave filter and DP-controller ability to keep the position in response to the wave, current and wind loads on the hull. Two moderate and severe JONSWAP sea states with $Hs = 1[m]$ & $Tp = 7[s]$ and $Hs = 2.5[m]$ & $Tp = 10[s]$ were simulated with $5[m/s]$ wind and $0.5[m/s]$ current. Crane wire tension, buoyancy force and magnitude of the wave force are shown in Figures 8a and Figure 8b, respectively. From the bottom panel of the figures it is evident that the longer waves of the $Hs = 2.5[m]$ sea state influence the payload for a longer time than in the $Hs = 1.0[m]$ case. The time spent in the wave zone is longer as shown in 'noisy' buoyancy force and resulting hull motions are evident as larger variability in the crane wire tension.

Figure 9a and Figure 9b show the magnitude of the wave and drag forces as a function of payload depth. Wave forces decrease with depth as suggested by Eq. 3. The drag forces in Eq. 1 depend on the relative velocity and will be affected by both crane tip motions propagating down to the payload and the current. It should be noted that the wave forces are exiting forces while drag forces act against the relative motion of the payload.

5 Discussion and Conclusion

This paper has demonstrated a practical example of how a synchronized sea-environment model can be included in a co-simulation. The sea-environment model is accompanied by a hierarchical specification of synchronization levels to clearly identify which parts of the environment description are shared between models. The choice of converting the frequency-domain wave spectrum to time-domain before transmitting individual wave components

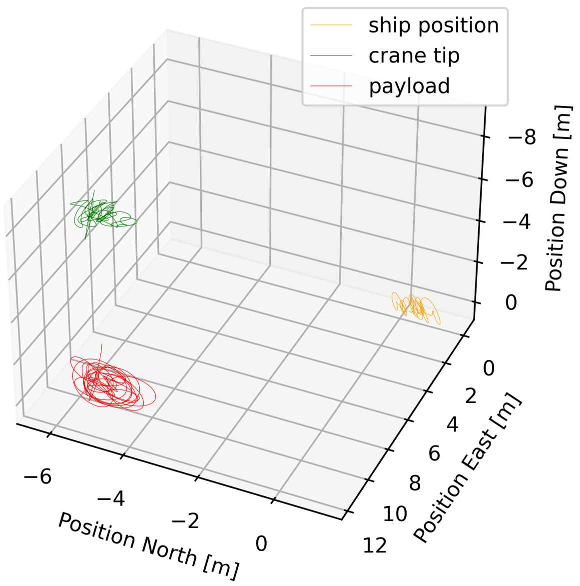

Figure 6. Position of the vessel centre of gravity, crane tip and payload. Cyan dots show the element centres for main wire and slings

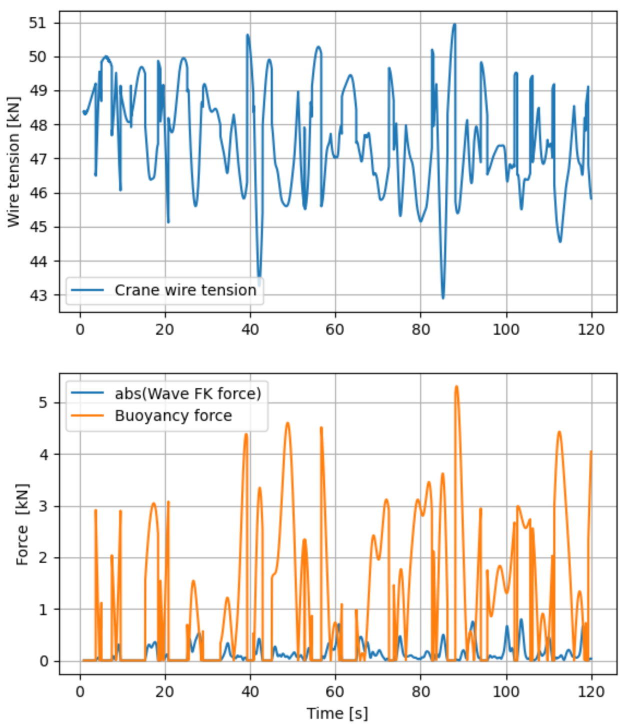

Figure 7. Crane and payload forces over 120 [s] as the payload hangs in the wave zone.

is an engineering approach that limits the model to linear wave theory. Linear wave theory is widely applied in ocean engineering, and this solution is compatible with common methods for evaluating sea-keeping and allows the models to apply Eq. 3 to derive wave properties, but limit the simulation to a description of the wave zone that relies on superposition to describe waves and current. The proposed interface in this paper does not preclude advanced methods for describing current and wind, pre-computed velocity fields can be read by the environment model and used to output magnitude and direction at any point. There is neither a necessity that the environment model is a ’pure’ model, as a model of a vessel can implement the environment interface and connect to models of propulsors and lifting equipment that interface with an environment a model description that is tightly coupled to the vessel geometry. However, only one model implementing the environment interface would be permissible in a co-simulation. The proposed interface place a large burden on the simulation developer since a great number of ports must be connected. The interface is not well suited for basic FMI v1 and FMI v2 tools due to the large number of interconnections required, it is technically possible but the workload on the simulation developer would be excessive and negate many of the advantages of GUI tools. Software with special features such as VariableGroups in ’cosim’ allows easy coupling of models to the environment, and FMI v3 with vector ports would negate the need for extensions in the co-simulation software. Usage of the port system for exchange waves components is not necessarily required as a shared library for computing wave spectrum values, randomly sampling them and computing phase angles can be developed. Control of the random number generator is necessary in such approaches to ensure that random phase angles, frequency and direction random samples are identical between models. It would be difficult to verify that all models actually used the shared library, and that each instance of the library is of the same version as time progresses, and from the authors perspective this would allow for version drift between models and limit the selection of simulation environment where models interfacing with the environment could be developed. An attractive property of transmitting wave components on ports is when components are sorted by amplitude a reduced number of components would mean a reduced fidelity wave field prioritizing the the most energetic waves. Propulsor interaction in co-simulation is a difficult problem as the interaction and loss effects are interdependent on wave conditions (distance from surface), geometries (hull surfaces) and other propulsors (jet and flow effects). One method would be to extend the linear superposition of wave particle velocities to propeller jets superimpose propeller jet velocities on a volume downstream of the propulsor. This would allow propulsor jets to influence other objects and change the inflow conditions of propulsors in the jet, but would not be sufficient to capture the interaction effects between jets influencing the flow patterns and in-

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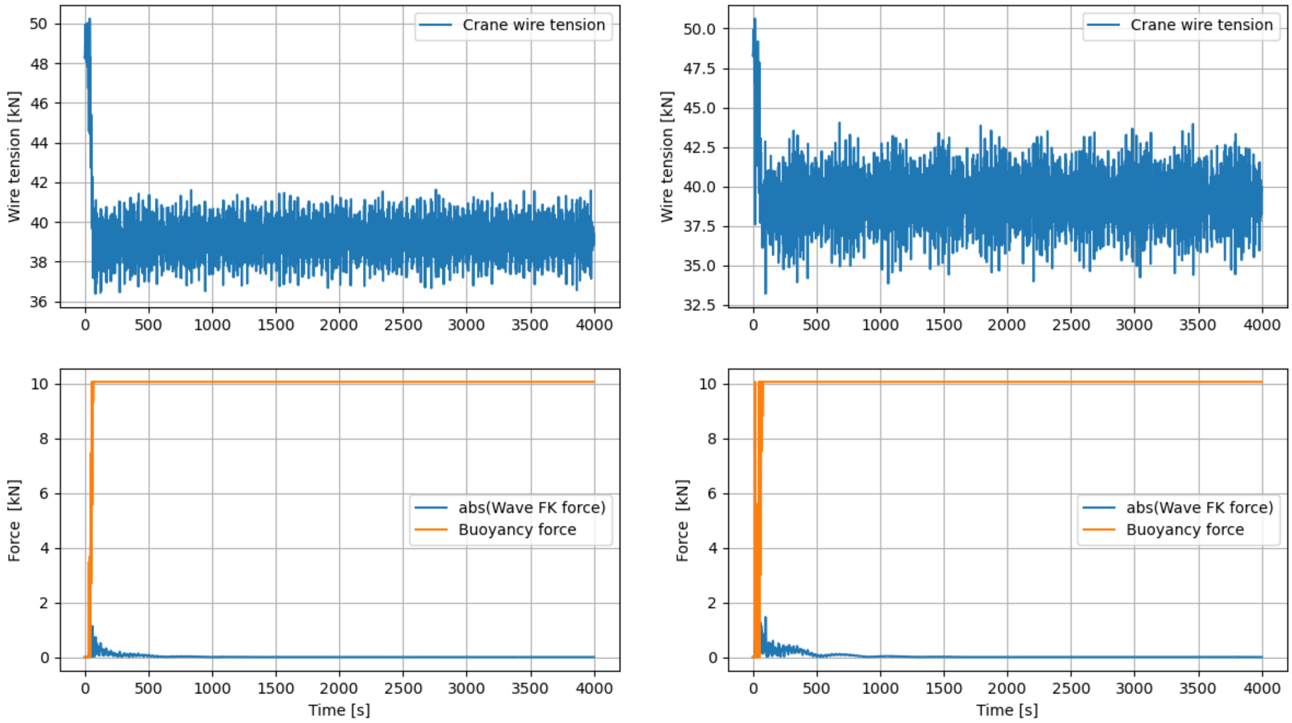
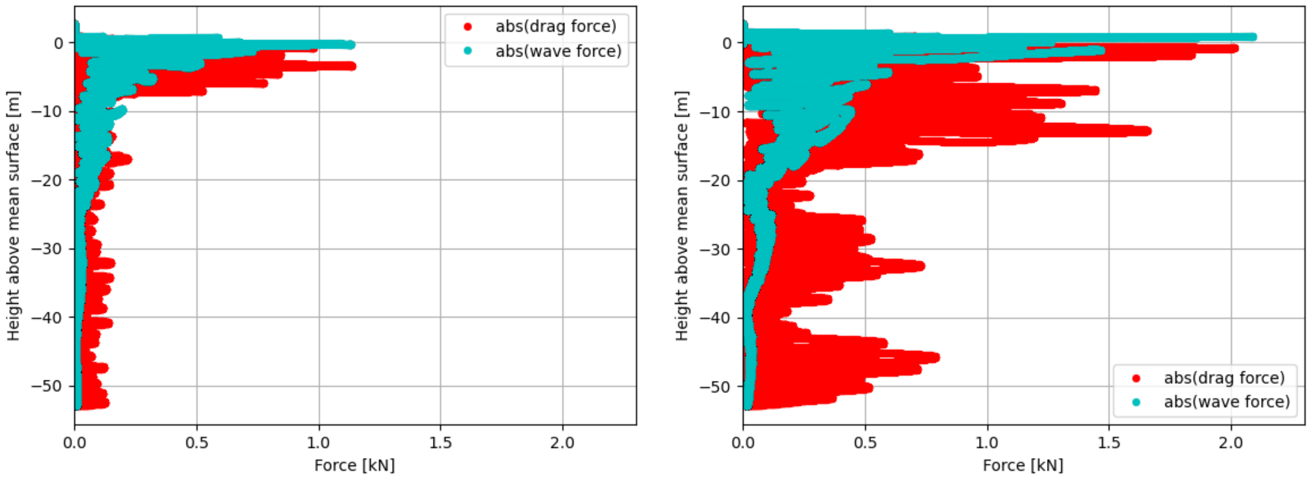


(a) Hs=1$[m]$ Tp=7$[s]$. **(b)** $H_s = 2.5[m]$ and $T_p = 10[s]$.

Figure 8. Crane and payload forces over 1200 [s] as the payload is lowered through the wave zone and down into the ocean.



(a) Hs=1$[m]$ Tp=7$[s]$. **(b)** $H_s = 2.5[m]$ and $T_p = 10[s]$.

Figure 9. Payload wave and drag forces as a function of water depth over 1200 [s] as the payload is lowered through the wave zone and down into the ocean.

teraction between propulsor jets and hull surfaces. The co-simulation model in this paper is fairly complete, but simplified. In general, the global thrust vector command from the DP controller must be transformed to local thrust forces and distributed to all the available, and operating, propulsors. This is done using a thrust allocation algorithm (which can be a simple thrust allocation matrix in some special cases). Such a setup is shown in (Skjong and Pedersen 2017b) where the thrust allocation is formulated as a non-angular *Model Predictive Control* (MPC) problem to be solved. The payload model include first order wave forces, but not the larger slamming forces experienced during wave impacts in the wave zone. Slamming pressure is larger than the regular dynamic pressure in the wave and must be accounted for in decision support applications. The proposed interface enables software such as 'cosim' to detect and verify the environment specification level for the co simulation. Common physical parameters, wind and current input with or without position feedback would be interpreted as specification level 0, 1 and 2 receptively while input of wave components would place the co-simulation at level 3. This also enables a partition of the models in the co-simulation into models participating in a sea environment, while models representing for instance control systems are identified as not directly influenced. The work on developing a sea-environment specification has highlighted the need for a reference frame specification. Different disciplines and application areas have different traditions for axis systems, and this makes verification of the wind, current and wave forces important as the simulation developer in principle can be without access to the source code of the models in the co-simulation.

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