Virtual Prototyping for Maritime Winch Design and Operations based on Functional Mock-up Interface Co-simulation

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Modern winch systems have become increasingly complex with hybrid power systems, intelligent control systems, and lightweight synthetic cables with complicated traction and handling mechanisms. The performance and stability of winch system operations relies on many factors. During early design phase, it is hard to manage a large set of parameters for system design exploration and optimization by traditional trial-and-error approaches. Virtual prototyping provides the users with numerous risk-free possibilities to evaluate the design trade-offs and immediately know the results of any modification. Simulations in virtual environment allow the users to predict and prevent inadequate design alternatives as early as possible, therefore save time and cost. This requires flexible, effective modelling of the dynamic system and efficient handling of the simulation. Our previous work has developed a virtual prototyping framework for complex dynamic systems based on the functional mock-up interface co-simulation standard. This paper presents the implementation of a virtual winch prototyping tool for maritime winch design and operations. Model development and setups for co-simulation are described based on an active heave compensated winch with hybrid drive system and secondary control. Simulation management and user interface is implemented based on web technology and connected to the functional mock-up units as clients through the WebSocket protocol.

Keywords: virtual prototyping, maritime winch, FMI co-simulation, hydraulic, secondary control, active heave compensation

Introduction

Maritime winches are widely used in offshore and subsea applications for operations such as hoisting and lifting, launching and retrieving, anchor handling, mooring, and towing. Winch systems may appear simple and winch control may seem straightforward because they operate in a single degree of freedom. But maritime winch operations are inherently challenging due to the impacts of potentially heavy loading conditions and external environment disturbances on the winch drum, gearbox, and cable packing and wearing issues (Takagawa 2010). As a result, modern winch operations require precise monitoring and control of the cable payout speed, length, and tension to provide such features as active heave compensation (AHC) within the splash zone, during water entry and landing on the seabed in subsea installations.

Major improvements in the drive systems have had profound impacts on winch operations today. Both electrical drive systems and low-speed-high-torque hydraulic drive systems have become available providing improved performances in terms of speed control and system efficiency (Nordaas 2017). However, these improvements also complicate the process for product and system design, including model development and simulation. General system performance and stability rely on many factors including the power systems, the mechanical components and the control algorithms. Many parameters are dependent on each other. Consequently, product and system design becomes iterative, and iterative process, cross-stages iterations in particular, are costly and time-consuming for product development.

Current winch design analysis relies on empirical operational experience and well-established in-house design calculations, using proprietary software tools to model operational scenarios and provide realistic dynamics. These tools can provide detailed functional analysis not in a similar level envisaged by the authors, however are usually expensive and require significant skill level and training to obtain useful results. General modelling and simulation tools like Matlab require significant model set-up time as well as good product operational knowledge. This paper presents a virtual winch prototyping (VWP) tool based on the proposed VP framework. The VWP tool on the web offers convenient parametrical manipulation of the system configuration for design exploration and control algorithm verification. Modelling of the complete system dynamics provides the user with comprehensive insights into the behaviours of the physical system during operation.

The rest of the paper is organized as follows: first, recent studies on maritime winch systems are discussed. Second, the proposed VP framework is described. Next, model development of the winch system and simulation setup for the implementation of the winch simulator are presented. Then, simulation results are discussed through a demonstration case. Finally, the conclusions and potential future work are given.

Related work

Recent publications on maritime winch systems include studies on cable control for ship mooring winch system considering the cable motions as uncertainty (Kim 2014). From the conducted experimental results, a representative model for the dynamics of the cable as a transfer function was obtained. It represents one typical approach in modelling and simulation of complex operation systems. That is to isolate the problem of interest and simplify the mathematical model to represent the physical systems using, for example, transfer functions, when simulation of full-scale model is not possible. This approach, however, does not provide the whole simulation scenario and requires valid experimental design and to obtain the cost coefficients. Other single-tool solutions can be found addressing different problems for winch system design and operations. Skjong and Pedersen presented model-based design for evaluating the control algorithms of offshore hydraulic winch systems (Skjong and Pedersen 2016). The authors developed dynamic models of the winch system using the Bond Graph (BG) method, which is an equation-based graphical modelling technique based on the energetic structure of physical dynamic systems. Using the model, the proposed sliding-mode back-stepping control method was evaluated and compared with regular PID-control. Further at a more detailed level, Wöll et al. performed sensitivity analysis on the drivetrain of an AHC winch, specifically, the gear centre distance and the ambient temperature (Wöll et al. 2017). It is shown that the lifetime of gear stage can be changed by -50% to +125% only by changing the centre distance, and small changes of the ambient temperature might lead to large deviations in lifetime for the bearings.

Virtual prototyping (VP) provides the designer a lot of possibilities to test and evaluate the design trade-offs and immediately knowing the results of any change. For general conceptual design purpose, Bye et al. presented a web-based tool for winch design optimization (Bye et al. 2017). The program is directly written in java, which makes it more open and flexible; however, the implementation of modelling is poor and ambiguous to understand for the user. In fact, the physics of the dynamic systems are merely simple calculations of the output torques of the drive motors. Using this primitive tool, Hameed et al. implemented a Matlab optimization client and employed four different optimization algorithms as comparison (Hameed et al. 2017). The results provide useful information for decision-making during the conceptual design phase of the winch system to obtain the most output torque using minimal electrical power. Previous work has developed a VP system for complex dynamic systems using the functional mockup interface (FMI) standard (Chu et al. 2017). Co-simulation provides an effective solution for real-time simulation of complex multi-domain models. It allows for the reuse of the existing knowledge in domain-specific modelling and simulation, and enhanced simulation performance of complex multi-domain dynamic system operations. Chen et al. presented simulation of heave compensated winch using a commercial software AMESim interoperate with ADMAS (Chen et al. 2017). AMEsim includes ready-to-use multi-physics libraries and can be easily coupled with other software packages including the FMI support.

Model development of the dynamic systems presented in this paper is based on an AHC winch with secondary control and is represented using the BG method. Model implementation and exportation for FMI co-simulation is handled by 20-sim as clients. User interface (UI) for winch design and operations including simulation management and visualizations is established based on web technology and communicates with the co-simulation clients via WebSocket protocol. The proposed approach provides a basis for a family of design assist tools targeted at the offshore industry, not only for winch design, but also for other complex machines for launch and recovery of subsea equipment. The offshore industry supply chain has been historically highly sensitive to economic cycles and will no doubt continue to be like this in the near to mid-term future. Consequently, competition tends to be keen and there is a general reluctance to invest in high-cost design tools which may not be proved economically viable. A low-cost, easy-to-use tool set based on established standards offers an attractive alternative to the established design methods currently available.

Virtual Winch Prototyping Framework

FMI is a tool-independent standard to support both model exchange and co-simulation of dynamic models using a combination of xml-files and compiled C-code (Modelica Associate, 2014). Since the first release in 2010, the FMI standard is now supported by over 106 tools and is increasingly adopted by automotive and non-automotive organizations worldwide. Such tools generate and export a sub-system or component as a functional mock-up unit (FMU) that can be imported and executed in another environment. In this way, several FMUs can cooperate at runtime through either model exchange or co-simulation in the same environment. The main difference is that an FMU for model exchange is simulated using the importing tool's solver, while an FMU for co-simulation is shipped with its own solver. Figure 1 illustrates the software architecture of the VWP framework. It consists of three layers. The component layer contains the dynamic models of the hydraulic power system and mechanical motion dynamics of the winch system. These sub-systems can be handled as one single FMU or they can be divided further down to the component level as needed. It is up to the users to decide the exportation of the FMUs; however, splitting strongly-coupled systems is usually not recommended for the reason of potentially compromised simulation stability. The winch controllers can be included as separate FMUs for convenient click-and-run in the VWP tool, preferably when multiple alternatives exist. It's also possible to program the control algorithms directly in the integration layer as part of simulation management.

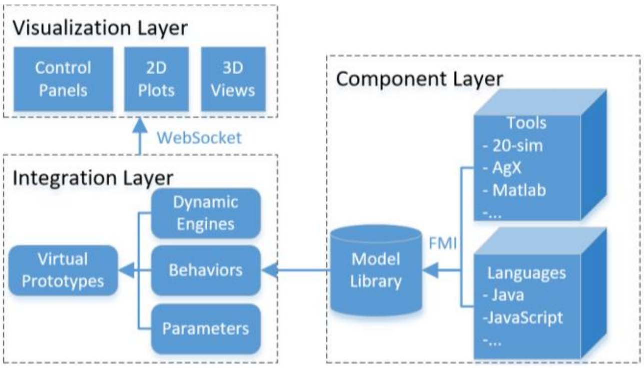


Figure 1. Virtual winch prototyping framework

The integration layer implements the system model and acts as the master for co-simulations with the co-simulation slaves running in the component layer. In the component layer, we use a thin Java wrapper around the FMUs to export the functionality via the remote method invocation (RMI). This allows for the possibility to distribute FMUs via the network, and to support FMUs with different compilation targets. For example, an FMU compiled for Linux would run in a Linux box and accessed over RMI by the VP system running in Windows.

The core of the VP framework is rendering agnostic and effectively decoupled from the visualization layer. This is important for the reuse of the simulation models with different views (possibly in different locations), and to use the visualization code with different models. Specifically, the UI which consists of the design/control management panels and 2D/3D views of simulations, must be portable and accessible to many different platforms and operating control systems. This is facilitated by using the web technology, which offers 2D/3D graphical visualizations using WebGL and turns the web-browser into a powerful visualization vehicle. Real-time bi-directional communication between the visualization layer and the integration layer is facilitated by using the WebSocket protocol, while static files are served using HTTP. The JSON RPC standard has been used to facilitate the data transmission between the clients and the server.

Model development of the winch system dynamics

A common way to control the winch movement is using the main pump to rotate the winch drum back and forth, as shown in Figure 2. The pump must build up pressure on either side of the motor to create adequate torque in one direction. When the movement in the other direction is needed, the pump must reduce the pressure on that side and increase the pressure on the other side. This forces the pump to work against the hydraulic compression every time a change in the rotational speed or direction is required. Consequently, this causes a significant delay in the efforts to control the motion of the winch drum. Controlling on the primary side also has a big drawback that a certain amount of flow is always needed to rotate the winch drum a certain angle. This results in over dimensioning of the pumps when lightweight loading at high speed is wanted.

On the contrary, secondary control means that the system is controlled in the place close to the winch drum rather than the pump, as shown in Figure 3. Secondary control uses variable displacement motor, which can provide the output torque and flow as required by adjusting its size. This is done by controlling the swash-plate-angle of the axial piston motor. Therefore, the pump will only have to keep a constant pressure during operation. As a result, there is no effect from hydraulic compression and no time delay from increasing pressure. In addition, an accumulator is usually added to restore the lost kinetic energy during decelerating and braking time, thus to save energy and improve overall system efficiency. Secondary control is one of the most energy efficient ways to control the winch drum motion for active heave compensation (AHC) operations. Since the size of the motor is always adapted to the needed torque, there is no need to over dimension the pumps. There is minimized pressure drops from control valves or other controlling devices. The response characteristics of the system are much better than using primary control. What's more, secondary control provides the possibilities in making advanced operating modes such as tension control (Z. Dabing 2011; Do and Ahn 2013).

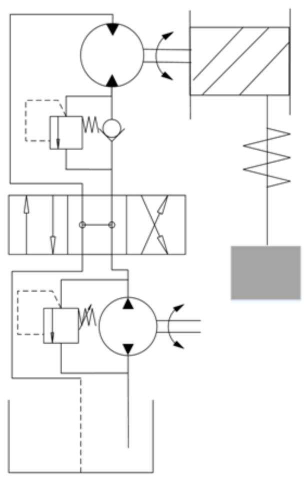


Figure 2. Primary valve control winch

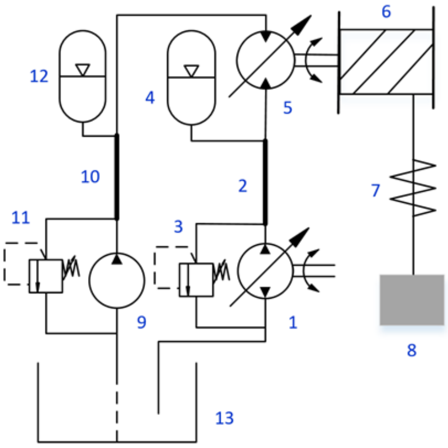


Figure 3. Secondary control active heave compensated winch

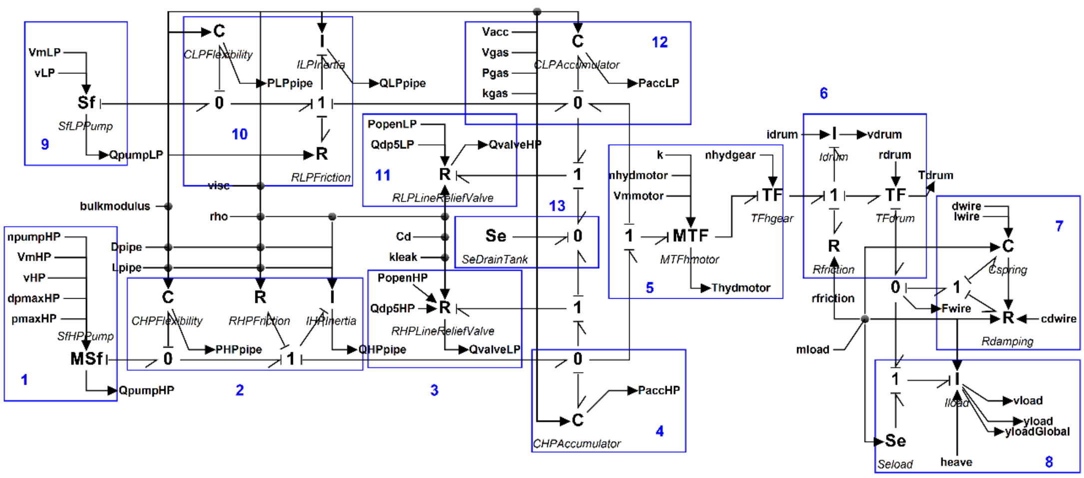


Figure 4. Bond Graph model representation of the active heave compensated winch system with secondary control

As an example for the VWP tool, model development of the hydraulic power system and motion dynamics of the winch including the cable and payload is based on the AHC winch with secondary control. Model representation and implementation of the system are established using the BG method, which is an equation-based modelling technique for multi-domain dynamic systems (Karnopp et al. 2012). It uses generalized power coordinates (i.e., flow and effort) to represent the power transmission between the physical components in various energy domains by identifying the energetic structure and decomposition of the physical system.

The BG model representation of the secondary control winch system is shown in Figure 4. These are corelated to and include the hydraulic components, fluid dynamics and mechanical components of the winch system in Figure 3. As can be seen in Figure 4, a variety of BG elements and junctions are used. Basically, source elements (Sf, MSf, Se) represent either flow or effort source, which in hydraulic domain are defined as volumetric flow and pressure, and in mechanical domain as velocity and force. Energy storage elements (C, I) represents the components or physical properties that store energy. For example, in the hydraulic domain these are the compressibility of the fluid, the inertia effect of the flow flux, and in the mechanical domain these include the compressibility of the cable and the inertia of the winch drum and payload. Energy dissipation elements (R) represent the components or physical properties that dissipate energy such as frictions, pressure drops over the valves. Transformers (TF, MTF) transfer power from one domain (or component) to another. For example, the modulated transformer (MTF) represents the variable displacement hydraulic motor which converts hydraulic pressure to torque and then through the gear transmission (TF) and winch drum (TF) to translational lifting force to the cable. There are two types of junctions in the BG method represented by 0 and 1 that sum up and distribute the flow and effort to the connected components. Transformers and junctions neither store nor dissipate energy. The causality of the simulation model for computation is defined and these are represented by the short strokes at either end of the half-arrows (bonds). Specifically, at the end of the causality the flow is decided and thus the effort must be given, and vice versa. The full arrows represent internal and external signals that neither contain nor transfer energy.

Due to the size limitation of the paper, the derivation of these BG elements representing the active heave compensated winch are not presented. Previous publications can be found on how to establish the constitutive equations using the BG method for similar systems (Chu et al. 2014, 2016). The BG model representing the winch system is exported and handled as a co-simulation FMU by a software tool called 20-sim. Different controllers are implemented as separate FMUs for convenience, including direct feedforward control, classic PI-control and AHC control. For the convenience of data distribution, the parametrical dimensions for design exploration, control and operational manipulation are extracted as the input variables, and the behavioural states are taken as output variables.

User interface design

The VWP designer tool is implemented as a web application written in JavaScript using “Bootstrap”, “Chart.js” and “Three.js” API/libraries for rendering visualizations. As shown in Figure 5, the current UI design consists of three sections, from the left to the right, simulation management, behavioural states, and 2D/3D graphical visualizations. The simulation management section allows the user to specify such as simulation time, macro-step size, external input signals, and most importantly, parametrization of the system models and behavioural state variables. These parameters ad variables are extracted from the dynamic models of the system and grouped by each FMU. For example, the presented implementation of the secondary controlled winch system has two FMUs, as shown in Figure 6: the controller that is a regular PI-controller, and the winch which includes the hydraulic power system, the winch drum, the cable and payload.

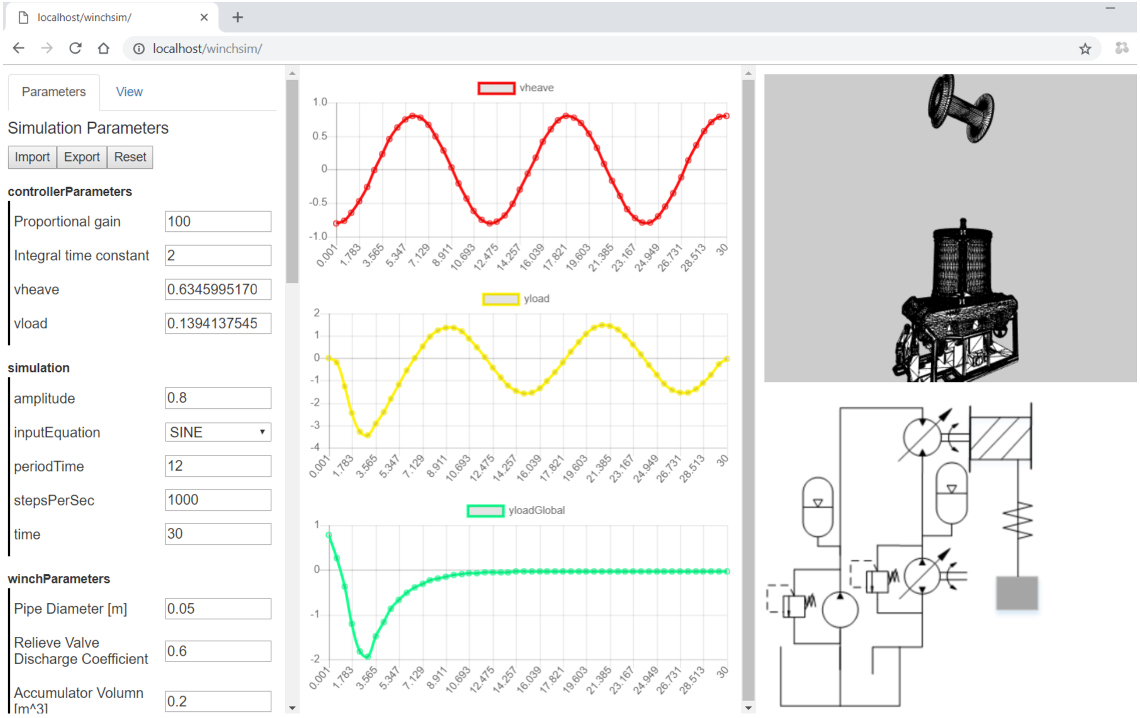


Figure 5. User interface design for winch system design and operations

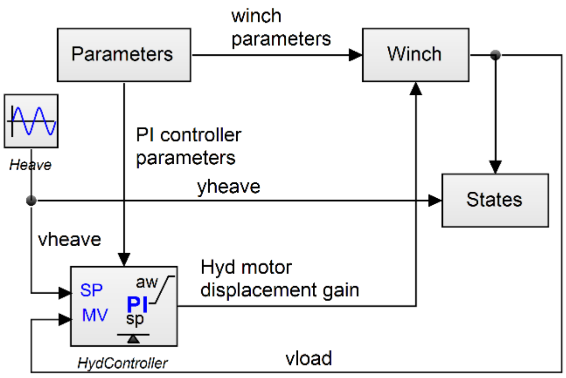


Figure 6. Model structure for the implementation of the VWP designer tool

This setup is mainly for the convenience to the reuse of the winch models with different controllers. The wave signal can be separated as another FMU which is probably the case when it is the obtained from real sensors. It is up to the user to determine on which level to set up the co-simulation scenario. Usually, strongly-coupled sub-systems should not be separated, for example the winch motor and the winch drum (Chu et al. 2017). Sub-systems that are numerically expensive to compute can be handled separately. For example, the cable with the payload could be a separate FMU from the one with the winch model. The mating of the interactive co-simulation FMUs depends on the model structure and I/O dependencies. The simulation master enforces an algorithm (i.e., master algorithm) that determines the coupling of the FMUs, the calling sequence and rate, etc. In this case, a fixed-step master algorithm is implemented following the FMI API, as given in Algorithm 1.

Algorithm 1: Fixed-step sequential calling sequence

```
Require: _startTime_ {simulation start time}
Require: _stopTime_ {simulation stop time)
Require: _stepSize_ {fixed simulation step size}
Require: [_controller, winch_] {FMUs to co-simulate}
init(controller, winch, startTime)
time <- startTime
while(time <= stopTime)
    doStep(winch, stepSize)
    controller.vload <- winch.vload
    controller.vheave <- periodicFunction()
    doStep(controller, stepSize)
    winch.k <- controller.displacementGain
    winch.heave <- controller.heave
    time <- time + stepSize
end while
for fmu in [_winch, controller_]
    terminate fmu
```

end for

Under the view tab, the user can choose what state variables to display at a desired sampling rate. These plots are also cross-referenced with the 2D block diagram to indicate which component the behavioural state belongs to. The visualization section on the right contains a 2D block diagram of the winch system and a 3D animation window. The iconic block diagram highlights the component when specifying the parameters of the system models in the simulation management section. 3D visualization provides the user with direct behavioural status of the winch and the suspended load during simulation. UI design is a time-consuming process which aims to provide the user convenient and comfortable access to desired information and manipulation. Therefore, its aesthetic design should serve for the user experience according to the ad hoc application.

Simulation results

Using the web-based prototyping tool, the user can easily change the dimensions of the system and see the results due to any change. For example, resizing the hydraulic pumps and/or motors by increasing its maximum displacement from 1 litre per revolution to 2 litre per revolution (l/rev) improves the response and stability of the AHC performance, as shown in Figure 7. However, capacity redundancy of the power system also means extra cost and more waste of energy.

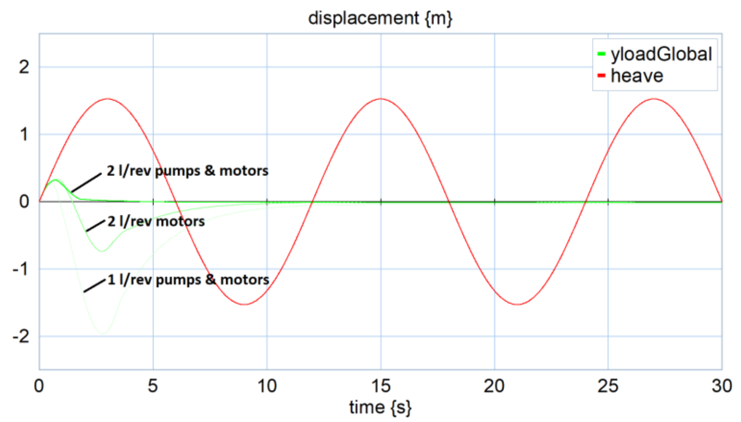


Figure 7. Load position during active heave compensation using double-sized motors

Co-simulation performance

Handling the co-simulation FMUs is realized using JavaFMI. One of the major motivations and benefits of using the FMI co-simulation approach for complex dynamic systems is enhanced simulation efficiency without compromising the complexity of modelling to represent the physics and dynamics of the system. This is in particular crucial for real-time operation systems. However, it is important to validate the co-simulation results and ensure the simulation accuracy loss within the acceptable range when taking a larger step size between the interactive co-simulation FMUs.

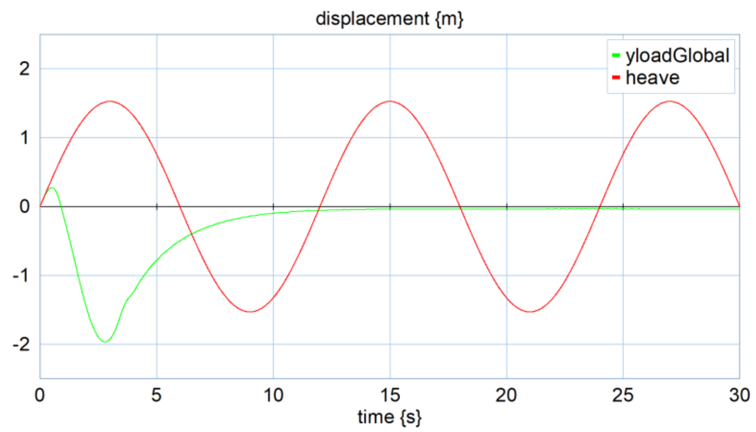
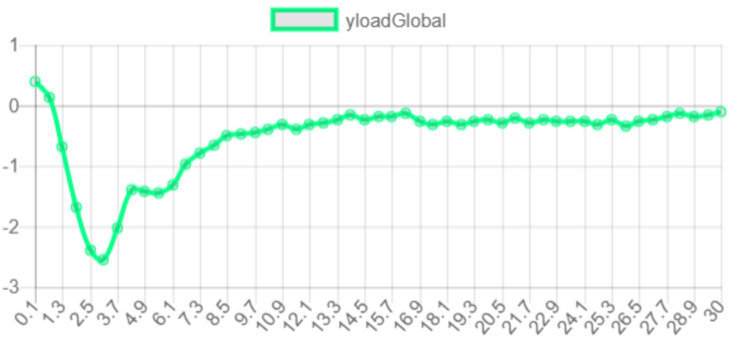
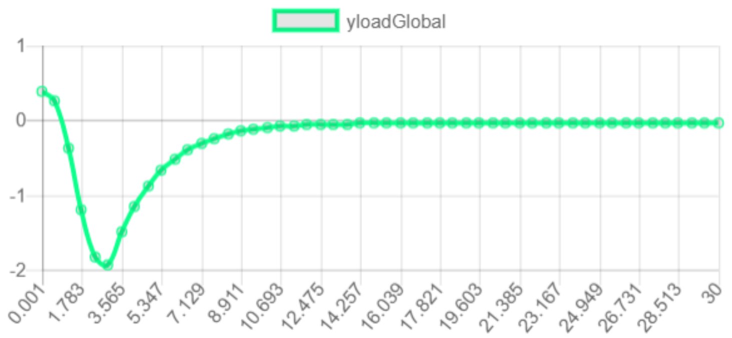


Figure 8. Simulation of the load position during active heave compensation in 20-sim



(a) Macro-step size 0.1s, frequency 10 Hz



(b) Macro-step size 0.001s, frequency 1000 Hz

Figure 9. Co-simulation of the Load position during active heave compensation co-simulation in the VWP tool

Given a regular sign wave to represent the heave motion, Figure 8 shows the load position during operations using the secondary control AHC winch. The load position was stabilized by rotating the winch (except the initial drop due to the weight of the payload and the compliance of the lifting wire). As shown in Figure 9, the VWP tool using the co-simulation approach generates validated results compared to the results in the integrated model in 20-sim. The co-simulation time step (also called macro-step) plays a crucial role for the efficiency and accuracy of the simulation. A finer step size usually generates results that are more accurate; however, takes longer time to compute. That in effect means the user may experience a few seconds delay for the computation, especially over long simulation periods. The simulation stability regarding computation efficiency and accuracy is not only determined by the co-simulation step sizes, but also the interactive FMUs. How they are solved individually and the interfacing of the variables that depend on the models representing the system and the exporting and mating of the sub-models for co-simulation. These issues including advanced master algorithms for co-simulation are not discussed in this paper at the current stage of research.

Verification

Due to intellectual property protection, control systems of the secondary control hydraulic winch and testing logs of operations are not to be shared, therefore we cannot present validation for the above simulation model and the results to the physical system and real data. Validity is a property of modelling, while accuracy is a property of simulation. The results in previous section proved that using co-simulation it was possible to distribute the simulation of a complex system, improve the real-time capability of the simulation without simplifying the model complexity, and finally provide flexibility for modelling and design. The users are expected to provide validated wrapped-up models (FMUs) for co-simulation purposes, which is the primary objective of the FMI standard of interfacing between different simulation tools. The compared results from 20-sim showed that significant speedups of simulations can be achieved with small loss of accuracy. Real-time simulation is also the most crucial criteria where hardware-in-the-loop (controllers) and human-in-the-loop (operators) exist for operations.

Conclusions

VP provides the user with a lot of possibilities for design exploration, system optimization, verification, and risk-free simulation of critical operations like active heave compensation. One of the major challenges is interfacing of various domain models and simulation tools that are currently used for very good reasons. The web-based prototyping and simulation tool for maritime winch system design and operations is developed based on the application of the FMI co-simulation standard. The FMI co-simulation standard allows for efficient simulation coupling, particularly, of complex multi-domain dynamic systems that require intensive computations of the simulation models in real time. As a result, models with different domain-specialized simulation tools from different users can be used, reused and interconnected. Web-based simulation management and visualization is effectively connected to different clients through the WebSocket protocol and turns the web browser into a powerful visualization vehicle. This provides the user, specifically, the designers, system engineers and customers, a convenient tool during early design phases. Models with fully integrated physics are developed and simulated. It is shown that co-simulation is an effective and efficient approach for distributed simulation of complex systems.

Future work based on the use of the VWP tool include sensitivity analysis of the parametric dimensions of the winch system, study on the performances of different control algorithms for AHC, and optimizations to improve system efficiency and reduce energy consumption. The users could easily build up a model library for their systems to run in the simulator, however, the establishment and maintenance of such libraries demands extensive efforts over time. . UI design is another time-consuming task that needs input from the users to determine what features are favoured. Design optimisation algorithms could also be included as presented by Hameed et al. (Hameed et al. 2017). Finally, real data from lab experiments and preferably sea test could be obtained to validate the modelling and simulation results.

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