Rigid body modeling and motion control of offshore cranes performing heavy lift operations

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Problem

During installation of subsea structures or offshore wind turbines, structures or equipment are lifted off the deck of the installation vessel. They are then lowered through the splash zone and down to the seabed or hoisted towards the top of the structure for mounting. Safe handling and control of the operation is heavily influenced by weather conditions, integrated vessel and crane dynamics and the motion control and compensation capability of the crane system. Improved motion control for such operations are believed to extend the operability and hence lead to more cost-efficient marine operations. In that regard, the implementation of a tugger winch system is the focus of this research. Additionally, a simulation tool for combined vessel and crane dynamics is developed.

Introduction

In a previous master's thesis [1], a model crane was designed and built in the Marine Computational Mechanics Research Lab (MCMR-Lab) at the Department of Marine Technology. The design was based on offshore cranes utilized in the industry and was built in a scale of 1:25. During the design process, a simulation tool was developed using the bond graph language to verify the concept. The crane dynamics were developed through Lagrangian mechanics with a rigid body assumption. Due to the basic idea behind bond graph theory regarding exchange of power between systems [2], auxiliary equipment is easily interfaced with the crane dynamics. To that extent, the previously developed crane simulation tool is suitable for further implementation of different modules such as payloads and tugger winch systems.

Considering that the combined vessel and crane dynamics are of interest when evaluating the feasibility of the implemented actuators and control systems, the aforementioned crane simulation tool must be extended to include the six degrees of freedom that are introduced by a floating vessel. Hence, the modeling procedure presented in [3] is adapted and used as a basis when deriving the combined system dynamics. In addition to the interaction between the crane and vessel, the effect of the hydrodynamic loads induced by incident waves and currents must be included. Consequently, models for added mass, damping, restoring forces and wave excitation forces are implemented.

Models

The Lagrangian mechanics framework requires the definition of a set of generalized coordinates that uniquely describes the position and orientation of the system. Hence, the crane joint angles and the six degrees of freedom of the vessel are utilized. Then, the equations of motion can be derived through the kinetic and potential energy of the system. As stated in [3], applying a set of quasi-coordinates, which are related to the generalized velocities, is advantageous when implementing the combined crane and vessel dynamics in a bond graph environment. Note that a rigid body assumption is applied for both the crane and vessel.

Commonly, the finite element method has been utilized when modeling wire dynamics, but considering the model complexity another method is presented in [5]. It approximates the wire dynamics by modeling the wire as a series of lumped mass-spring-dampers. This simplification showed promising results in regards to precision and requirements to computational power.

To control the crane, an inverse dynamics controller [4] is implemented such that the crane tip is able to follow a reference signal retrieved from data provided by Subsea 7. With the control algorithm, the crane simulation model is able to mimic the motion of a real offshore operation, hence facilitating the testing of tugger winch systems.

References

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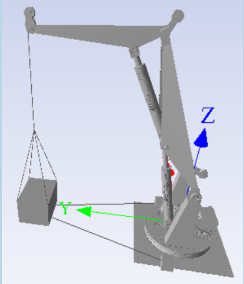
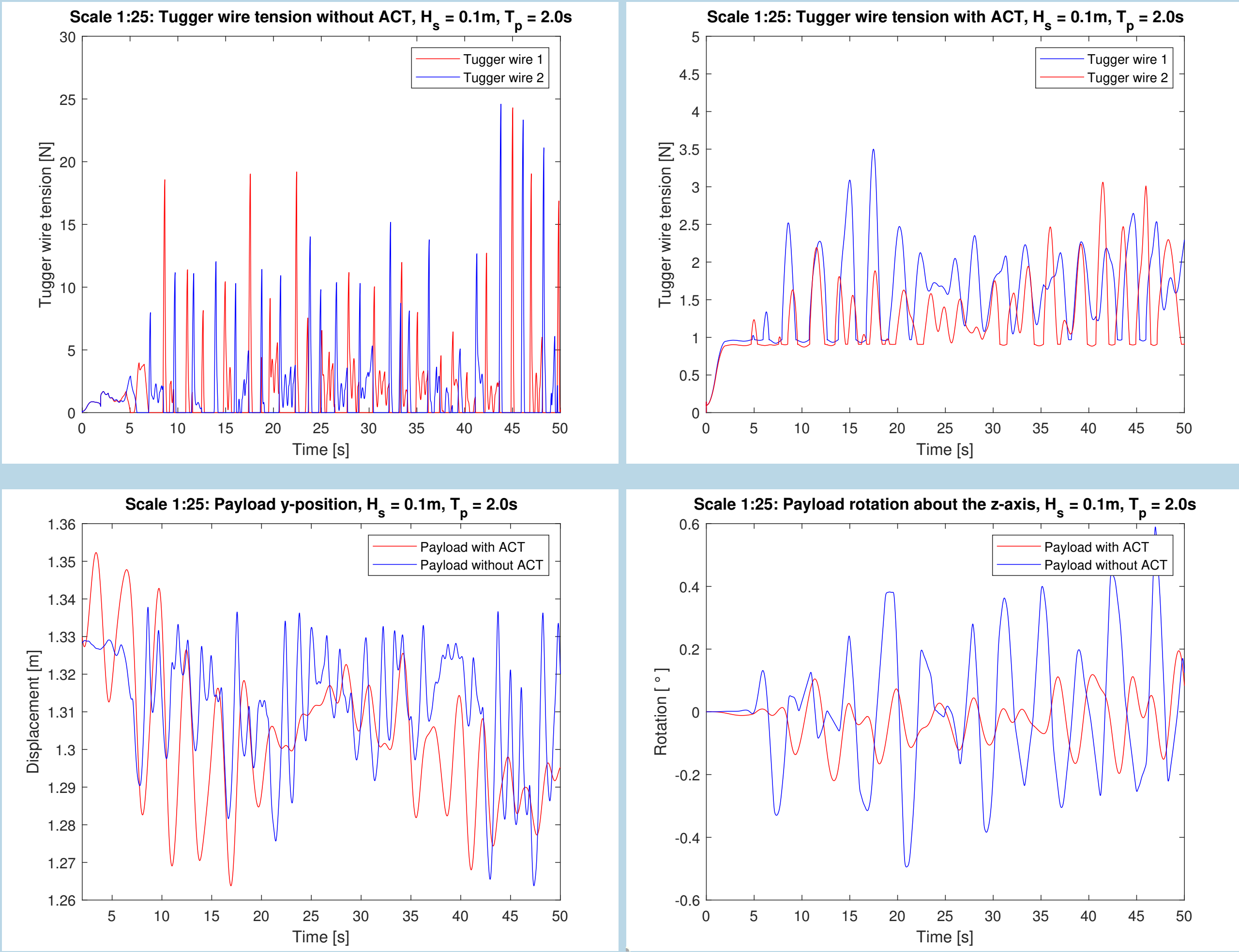
Results

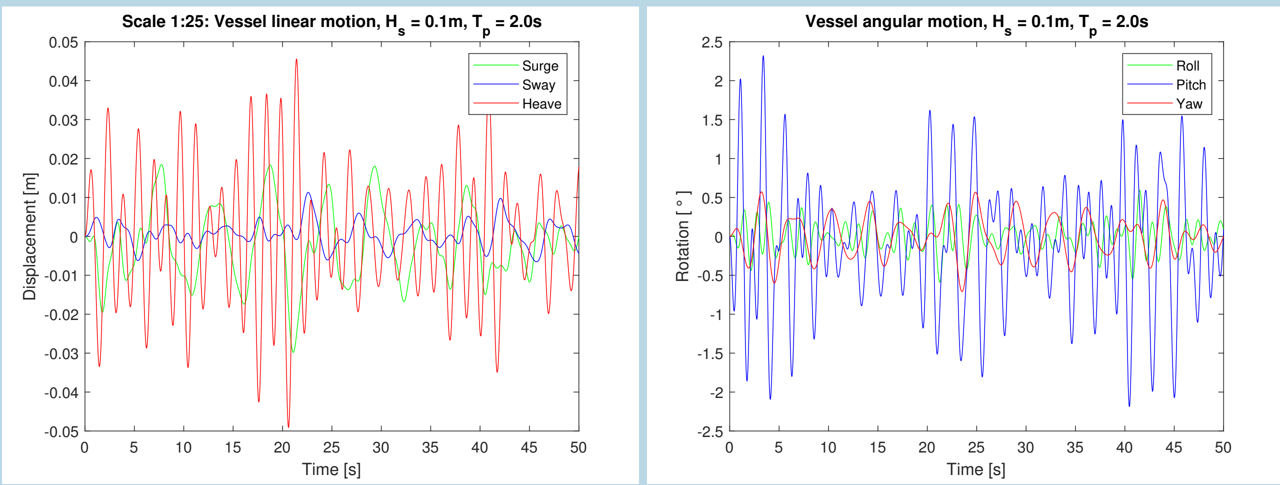
To verify the models and test the tugger winch system, the crane and payload configuration is based on an offshore operation. The payload is suspended from the crane tip and fastened to four slings, one at each corner. Two tugger wires are fastened to the payload to restrict the motion along the y-axis and an initial tension is applied to induce an initial angle of $-1.1°$. The setup is illustrated in the figure to the left.

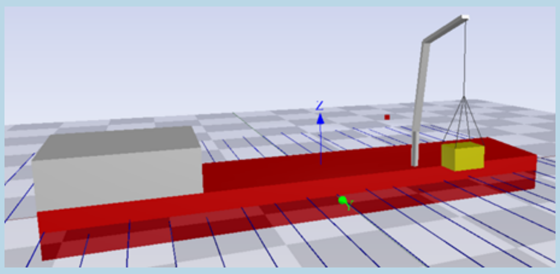


Then, the crane tip is set to follow a reference signal corresponding to the motion retrieved from a realistic scenario. Note that due to scaling, a sea state with significant wave height $H_s = 2.5m$ and peak period $T_p = 10s$ becomes $H_s = 0.1m$ and $T_p = 2.0s$. To illustrate the effect of tension controlled tugger wires, the loads in the tugger wires are shown with and without the control algorithm. When the wires have a fixed length, they are allowed to go slack and snap loads are therefore produced as the wire re-engages tension. Consequently, peak loads are observed in the plots. In the case where the controller is implemented, the wires are never allowed to go slack, hence snap loads are prevented. Furthermore, the tension in the wires are kept below the safe working load (SWL), which is designed to $6N$ in the model scale. Note that the payload motion is affected by the inclusion of tension control. Too avoid loads above the SWL, larger pendulum motions are occasionally allowed in the y-direction. On the other hand, the overall rotation about the z-axis is drastically reduced, which at times lead to pendulum motions of smaller magnitudes compared to the fixed wire length case. It should be mentioned that the tension control is able to prevent snap loads at rougher sea states and that the limiting factor is the allowed pendulum motion of the payload rather than tension in the wire.



The combined crane and vessel system is systematically developed as suggested in [3]. All vessel and hydrodynamic parameters are chosen in correspondence with the ship Seven Arctic [6]. Note that not all parameters are available, hence tuning of relevant experimental data is performed to obtain an expected vessel and crane behavior. Disregarding uncertainties in the parameters, the motion induced by incident waves were within reasonable amplitudes and frequencies, hence implying that the developed simulation tool functioned as expected. Note that the vessel is moored during the simulations.





To visualize the vessel and crane motion, the relevant system parameters are utilized to generate a 3D visualization of the simulation. The surface elevation of the propagating wave is given by horizontal lines to visualize the propagation along the x-axis. The illustration to the left shows the 3D model of the combined vessel and crane system in its initial configuration. The visualization tool serves as an additional instrument for verifying the behavior of the motion when working with the simulation model.

Conclusion

The implementation of tension control in the tugger winch systems prevent snap loads from occurring, but the chosen method is limited by the increased pendulum motions of the load. Hence, further improvements to the control algorithm is suggested as a mean to both prevent snap loads and reduce pendulum motion.

The motion of the vessel, which is induced by incident waves, correspond with the expected magnitudes for a moored vessel with dimensions that mimic the ship Seven Arctic. Furthermore, the crane tip moves as expected when its joints are fixed to their initial configurations and the crane tip moves according to the motion of the vessel. Hence, a simulation tool for further testing of the model crane in the MCMR-Lab has been developed.