# A Co-simulation Methodology for Risers Tensioned with Direct Acting Tensioners

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***Abstract*— In this paper, the development of a co-simulation methodology to simulate the coupled response of a platform connected to a riser through a basic Direct Acting Tensioner (DAT) is discussed. The hydro-pneumatic tensioner system is modeled in *SimulationX*, a widely used multiphysics software, while the platform and the riser stack are modeled in *OrcaFlex*, which is a well-known ocean engineering software package. The application programming interface (API) capabilities of both software are exploited to enable the development of the co-simulation model using an interface-file coded in *Python*. In the co-simulation, the *OrcaFlex* model is the master and the *SimulationX* model is the slave. A *winch-wire* element is used to represent the responses of the tensioner cylinder inside the *OrcaFlex* model. At the beginning of each simulation time interval in *OrcaFlex*, the kinetics at the bottom end of the *winch-wire* is transmitted as the force applied on the piston rod of the tensioner cylinder, at the end of the previous time-step, to *SimulationX*. The velocity of the piston-rod at the end of the previous time interval in *SimulationX* is then passed on as the payout rate of the *winch-wire* at the beginning of the current time-step in *OrcaFlex*. This process is repeated for the next time step, and the simulation proceeds until the end of the specified simulation time. A detailed discussion of the simulation results is included to showcase the advantages of the approach. The simulation files are made available for public access.**

***Index Terms*—riser tensioner, multiphysical systems, co-simulation, riser disconnect, ocean engineering**

## I. Introduction

Fig. 1 depicts a Direct Acting Tensioner (DAT) type riser tensioner system. We infer from the arrangement that a riser tensioner is required to: (i) isolate the riser from excessive loads due to the motion of the platform, (ii) maintain the required top tension to prevent the riser from buckling under self-weight, (iii) avoid excessive bending due to current loads, which hinders the drilling operation, and (iv) to ensure a clean lift-off of the lower marine riser package (LMRP) from the Blow Out Preventer (BOP), in a riser *disconnect* event [1].

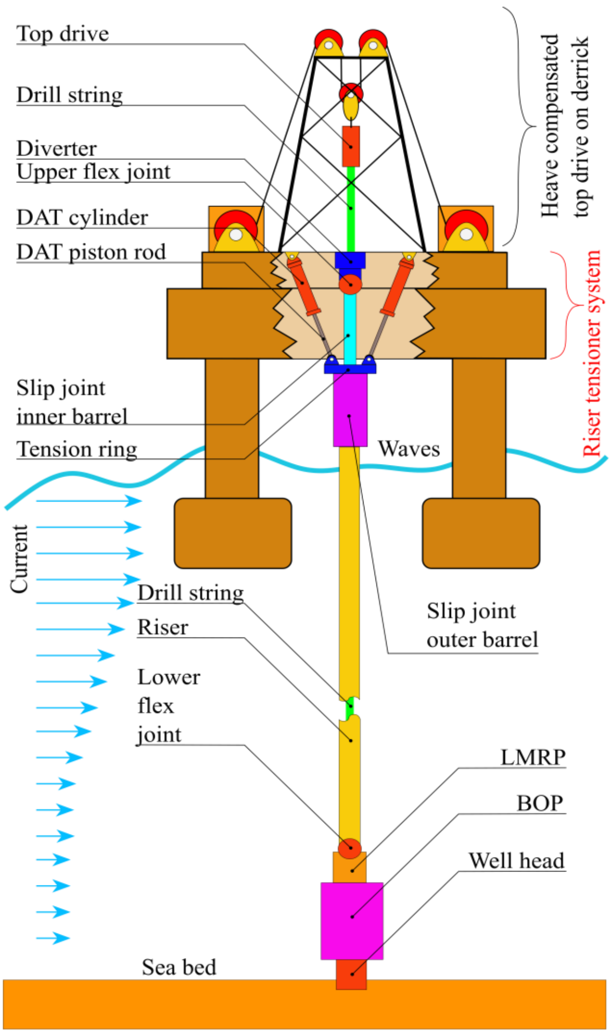


Figure 1. General arrangement of the riser tensioner system (DAT).

Guidelines for the analysis and operations of drilling risers can be found in ISO/TR 13624-2 [2], API RP 16Q [3], API Bulletin 5C3 [4], DNVGL ST F 201 [5] etc., while specifications for the tensioning equipment can be

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found in API RP 16F [6]. In general, the codes require analysis of the drilling riser in various states viz. *connected*, *recoil*, and *disconnected* [7, Sec. 9.2].

Commonly used software for riser analysis includes *OrcaFlex* from Orcina, *Riflex* from DNV-GL, *FLEXCOM* from MCS Kenny, and *Deeplines* from Principia-IFP. Though a bit dated, a review of the capabilities and limitations of some of the above packages are given by Zhan [8].

Suzuki and Tanaka [9] presents basic research on an anti-recoil system. Sullivan *et al.* [10] discusses the use of linear spring elements to model tensioner cylinders for drilling riser analysis. Lang *et al.* [11] discusses the development of a disconnect and recoil analysis software tool that has been integrated with a 3D FE model of the drilling riser system. Grytoyr *et al.* [12] presents a methodology for the dynamic analysis of a drilling riser disconnect and recoil using *Riflex* where the effect of the hydro-pneumatic riser tensioner system is accounted for by using the adiabatic gas equation and a *damper* model. Haziri and Dyngvold [13] formulates a mathematical model for the hydro-pneumatic wireline riser tensioner system to verify the performance of a multiphysical model of the tensioner system modeled in *SimulationX*. Wang and Liu [14] derives a mathematical model for the DAT system and implements this model into a hydrodynamic analysis package using user-defined subroutines. Sten *et al.* [1] formulates a parametric model for DAT cylinder tensions based on a multiphysical model of the cylinder in *SimulationX*. This parametric model is subsequently used in the final *Riflex* analysis to get an improved model for the tensioned riser response. They also propose the development of an integrated model that accounts for riser dynamics and pressure variation in the tensioner system. Guimaraes *et al.* [15] proposes non-linear, parallel, spring-damper scalar elements in series with a rigid beam element to represent the drilling riser tensioner behaviour during an emergency-disconnect scenario global-analysis performed using *OrcaFlex*. Wang and Gao [16] gives the 3D mechanical model and governing equations for the recoil response of a deep-water drilling riser based on the mass-spring-damper approach.

Conventionally, linear/non-linear spring elements available in the riser analysis packages are used to approximate the top tension applied by the hydro-pneumatic riser tensioner [15]. However, this is a simplification with significant impact on simulation output, especially in the recoil phase since the effects of the anti-recoil system is not captured effectively by these models. Further, the simplification of the multiphysical riser-tensioner system precludes the inclusion of elements that can cause the tensioner response to vary during a dynamic simulation.

The difficulties that we face in building a simulation model to capture the behaviour of the platform–tensioner–riser system in its entirety boils down to the following facts:

- Commonly used software for dynamic analysis of marine systems seldom has multiphysics capabilities to a level that permits the modeling of hydro-pneumatic tensioners and associated control systems.
- Commonly used multiphysics analysis software seldom has a hydrodynamics library that enables the modeling of fluid-structure interactions.

Given the strengths of each domain-specific generic software, developing a co-simulation interface brings down the brick wall that prevents the modeling of complex multidomain systems with a strong hydrodynamics component. This approach was suggested by Sten *et al.* in [1], and the present work is an attempt at developing a co-simulation model with real-time data exchange to facilitate the simulation of the integrated platform–tensioner–riser system, with the platform and riser being modelled in an FE-based ocean engineering software, and the hydro-pneumatic riser-tensioner being modelled in a multiphysics software.

The paper progresses with an introduction to the Direct Acting Tensioner (DAT) type riser-tensioner system. This is followed by an investigation into the avenues for developing a co-simulation interface between the platform and riser system modelled in *OrcaFlex v.11.0c*, and the hydro-pneumatic tensioner modelled in *SimulationX v.4.1*. We then model the *basic realistic system* with most of the components found on a top-tensioned riser system, carry out a fully coupled analysis using the co-simulation model, and discuss model performance.

The simulation files associated with all results discussed in the paper are available for download at:

https://www.dropbox.com/sh/cwqor6v9fnq3rmj/AABVHIjbjuKGnBiAJVo82tjna?dl=0

## II. The Riser Tensioner System

An overview of riser tensioner systems can be found in [11].

With reference to Fig. 1, we see that the top tension in a DAT type riser tensioner system is provided by hydropneumatic cylinders which, in conjunction with the slip joint (SJ) and the upper flex joint (UFJ), provide the mechanical interface between the platform and the riser. The *cap end* of each DAT cylinder is attached to the drill floor, while the piston rod, which protrudes through the *gland end*, is attached to the tension ring assembly mounted on the outer barrel of the slip joint. The connections are through shackles that are free to rotate and may be approximated as ball joints. The riser top end is in-turn rigidly attached to the lower end of the slip joint outer barrel, while its bottom end is attached to the BOP at the LMRP-BOP interface. The tension applied by the DAT cylinders is regulated by a hydro-pneumatic system. Fig. 2 shows the hydro-pneumatic system associated with a single DAT cylinder.

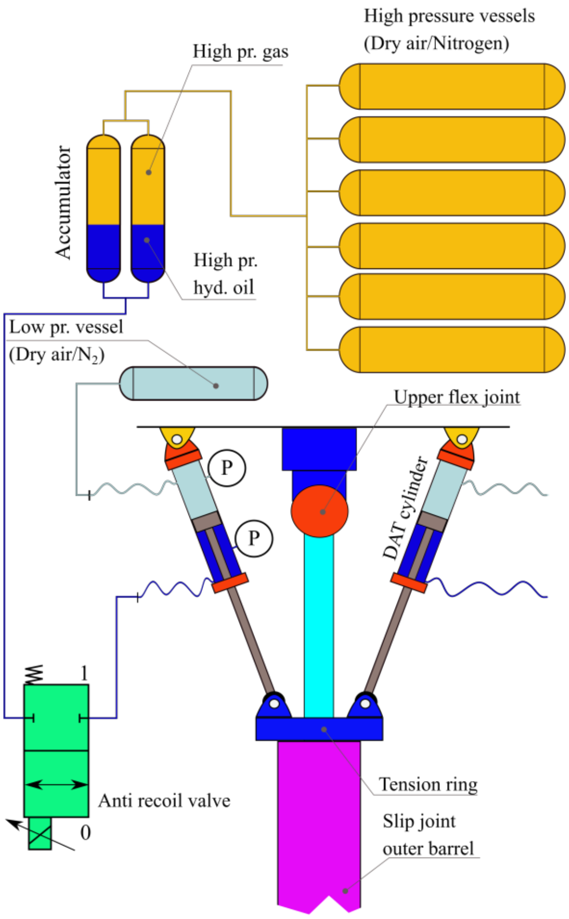



Figure 2. The hydropneumatic circuit.

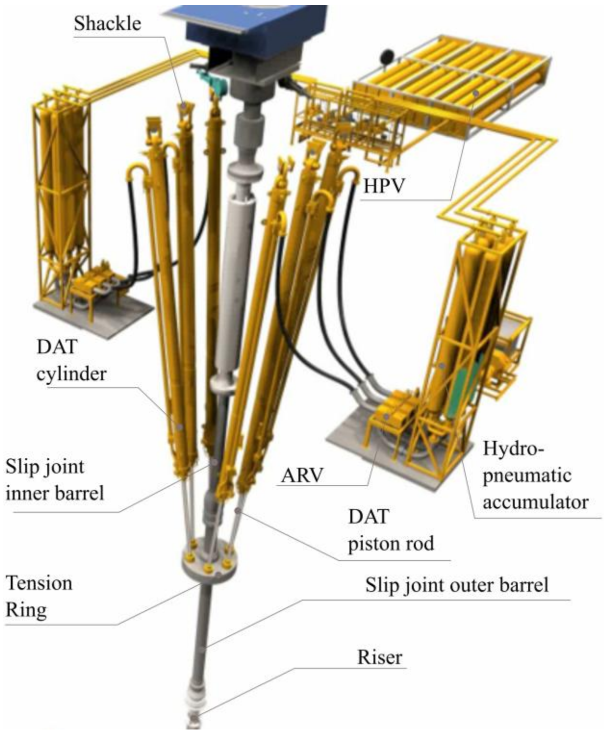



Figure 3. DAT system arrangement (courtesy NOV).

While Fig. 1 shows only two cylinders, there are usually six such cylinders in most systems, arranged as shown in Fig. 3.

As the platform moves along its 6 degrees of freedom (DoFs), in response to environmental loads, even with the restrictions imposed by the DP/mooring system, the distance and angle between the BOP and the diverter housing changes. The change in length is accommodated by the slip joint, while the riser tensioner system maintains a near constant pull on the top end of the riser. The upper and lower flex joints accommodate the changes in the angular displacement and limits the bending stresses.

Severe weather, mooring failure, or other operational reasons may cause/require the platform to move away from the connected operational limits of its location w.r.t. the well head. Before such an event occurs, the riser must be disconnected from the well head to avoid damage. This may be a planned disconnect, or an emergency disconnect, depending on the circumstances.

Before a planned disconnect, the drill string is raised out of the BOP, the BOP rams closed, the drilling mud in the riser is replaced with sea water, the drill string retrieved completely, and the LMRP disconnected from the BOP. The riser in this case is free flooding.

During an emergency disconnect, the shear rams of the BOP shear the drill string, and the LMRP is disconnected from the BOP. The drilling mud present in the riser is shed until seawater replaces it, and a part of the drill string is present inside the riser.

As the LMRP is disconnected from the BOP, the overpull exerted by the riser tensioner system and the residual elasticity in the riser, causes the riser to accelerate upwards. This is termed *riser recoil*.

The behaviour of the riser as it recoils is of importance since too slow a recoil increases the chance of the disconnected LMRP hitting the BOP as the platform-riser system moves under the influence of environmental loads, and too fast a recoil increases the chance of the DAT piston hitting end stroke, the SJ bottoming out, the outer barrel of the SJ jumping out of the tensioner ring, thereby causing damage to the drill floor.

The ARV is used to regulate the recoil behaviour by throttling the hydraulic oil flow, thereby reducing the speed of the riser as it accelerates upwards. However, excessive damping in the DAT cylinders causes compressive stresses in the riser stack, which might cause buckling, if high enough.

After the recoil phase, the riser is held in what is commonly referred to as the *soft hang-off* condition, where it is suspended from the platform, with the riser weight being supported by the DAT cylinders at mid-stroke [7, Sec.9.2.6.2.6].

In the following sections we present a co-simulation methodology to carry out fully coupled analysis of top tensioned risers in the *connected*, *recoil*, and *hang-off* modes.

## III. Synthesis of the Co-simulation Methodology

In looking at avenues that permit the development of a co-simulation interface, we notice that both *OrcaFlex* and *SimulationX* has Application Programming Interface (API) capabilities which may be enabled with *Python*, as discussed in [17].

Either the tension or the pay-out rate of the *winch* element of *OrcaFlex* can be specified by an external variable, and this opens up the following possibilities for co-simulation of the riser tensioner system:

- The *kinematic–kinetic* approach: Pass on the kinematics of the ends of the winch-wire from *OrcaFlex* at any time step, as tensioner piston kinematics to *SimulationX* through the *Python* interface, simulate the tensioner cylinder dynamics in *SimulationX*, and return the piston force as the winch-wire tension to *OrcaFlex*, which then simulates for the hydrodynamic/riser response for the following time step.
- The *kinetic–kinematic* approach: Pass on the kinetics of the ends of the winch-wire from *OrcaFlex* at any time step as external forces applied to the tensioner piston in *SimulationX* through the *Python* interface, simulate the tensioner cylinder dynamics in *SimulationX*, and return the piston velocity as the pay-out rate of the winchwire to *OrcaFlex*, which then simulates for the hydrodynamic/riser response for the following time step.

We notice that use of the *kinematic–kinetic* approach causes instabilities associated with hit of end-stroke events and hence we use the *kinetic–kinematic* approach in developing the co-simulation methodology presented here.

The README.txt available in the download has further information pertaining to software configuration and comprehension.

## IV. Modeling and Simulation of the Basic Realistic System

We proceed to model a realistic system that includes all the basic elements of the hydro-pneumatic tensioner, except the ARV. The *OrcaFlex* model for the platform and riser for the co-simulation of such a system is shown in Fig. 4, while the *SimulationX* model for the hydro-pneumatic tensioner system is shown in Fig. 5. The winch element is concealed beneath the tensioner cylinder arrangement in the *OrcaFlex* model, and we use the kinetic-kinematic approach to simulate for the system response in a simulation where the *OrcaFlex* model is the master and the *SimulationX* model is the slave. Also, since the *winch wire* in *OrcaFlex* cannot handle compressive loads, we make use of an end-stop arrangement in the model to emulate the effects of the tensioner piston hitting end stroke. An API interface file coded in *Python* is used to facilitate this communication between the *OrcaFlex* and *SimulationX* models.

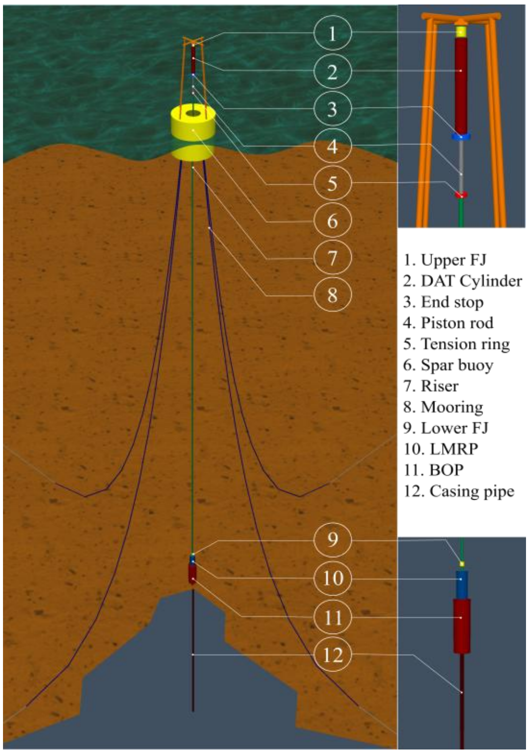



Figure 4. Concept of the basic realistic riser tensioner system.

As seen in Fig. 4, the riser extends from the LMRP to the tension ring through the moonpool of a moored spar buoy. The LMRP may be disconnected from the BOP to simulate the recoil response of the free flooding riser. The tensioner cylinder is connected directly to the tension ring, and hence a slip joint is not included, in this basic system.

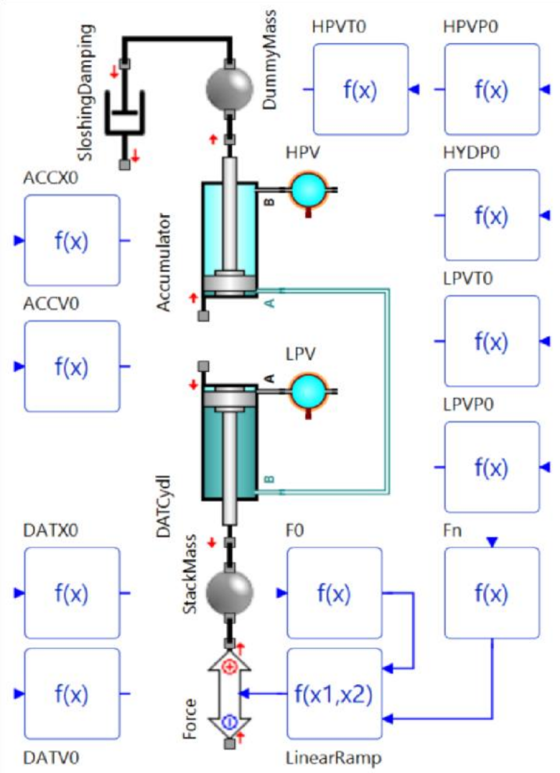



Figure 5. SimulationX component model of the hydro-pneumatic tensioner.

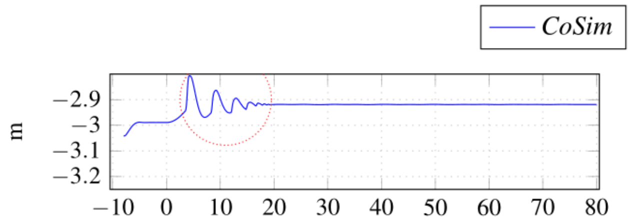
The tensioner cylinder in this case has dry air on the cap side and hydraulic oil on the gland side. As seen in Fig. 5, the pneumatic port of the tensioner cylinder is connected to a pressure vessel named the *LPV*. The hydraulic port of the tensioner is connected to a hydro-pneumatic accumulator modelled as a frictionless hydraulic cylinder with negligible piston mass. A damper is included to damp the oscillations of the oil-gas interface inside the accumulator. The pneumatic port of the accumulator is connected to another pressure vessel named the *HPV*, containing dry air. We consider heat transfer through the cylinders and the pressure vessels. Function *DATX0* is used to specify the initial stroke of the tensioner cylinder for each run of the *SimulationX* model, as and when it is invoked by the master *OrcaFlex* simulation. Similarly, *DATV0* specifies the initial piston velocity, *HPVP0* specifies the initial pressure in the HPV, *F0* specifies the initial force acting at the end of the piston rod, and *Fn* specifies the final piston force. Further, functions *ACCX0*, *ACCV0*, *LPVP0*, *LPVT0*, and *HPVT0* specifies initial values of the accumulator cylinder stroke, accumulator piston velocity, *LPV* pressure, *LPV* temperature, and *HPV* temperature respectively.

For any *OrcaFlex* simulation interval [$t_n$, $t_{n+1}$], the force acting on the top of the riser is passed on as the force $F_n$ acting on the piston rod at time $t_n$ in the *SimulationX* simulation interval [$t_{n-1}$, $t_n$]. The *SimulationX* model is then simulated, and the velocity of the piston at time $t_n$ is passed on as the payout rate of the *winch* element at time $t_n$ for the *OrcaFlex* simulation. For the first time step [$t_0$, $t_1$], the force acting on the top end of the riser is obtained from the static analysis results in *OrcaFlex*. The *SimulationX* model is simulated in the time interval [$t_{-1}$, $t_0$], where the force acting on the piston at $t_{-1}$ is assumed to have a value in the vicinity of the static analysis results in *OrcaFlex*. Since the riser stack mass is represented by a *mass* element in the *SimulationX* model, the inertial component has to be removed from the riser force passed on from the *OrcaFlex* model, and this is handled inside the interface file. Readers may refer to the interface file available in the download for details.

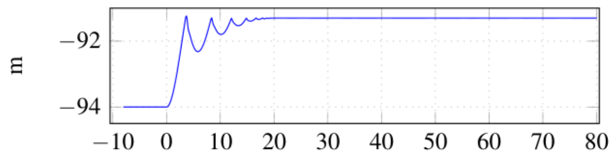
*OrcaFlex* and *SimulationX* results for the calm-water disconnect response of such a system is shown in Fig. 6, and Fig. 7 respectively.

Here, the LPV volume is 0.5 $m^3$, HPV volume is 10 $m^3$, and the initial temperatures of both the LPV and HPV are 20 ℃. The LPV and HPV pressures being 1.05 bar and 31.05 bar, respectively. Other details may be found inside the model files.

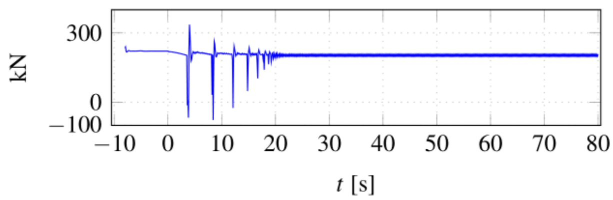
The corresponding response of the hydro-pneumatic tensioner system modeled in *SimulationX* can be observed in Fig. 7. We note that, as the tensioner cylinder retracts, the HPV pressure falls and the LPV pressure climbs. The piston hits end-stroke a few times before coming to rest at the end stroke. Since we consider heat transfer across the walls of the pressure vessels, tensioner cylinder, and the accumulator, we see that the LPV temperature, after rising as the cylinder retracts, begins to drop as heat is transferred out from the gas. On the HPV side, we note that the temperature drops initially as the cylinder retracts, and then begins to climb as heat is absorbed from the surroundings. Pressure variations corresponding to this temperature variation is also present. We also note that the cylinder force is also slightly lower after the disconnect, the scale of the graph prevents easy comprehension of this effect. Also, as a consequence of the co-simulation methodology, the cylinder force fluctuates about a mean value, and this effect, which is more pronounced after the disconnect, is the cause of the slightly thicker plot lines in Fig.s 6c and 7b.




(a) Buoy draft (m)



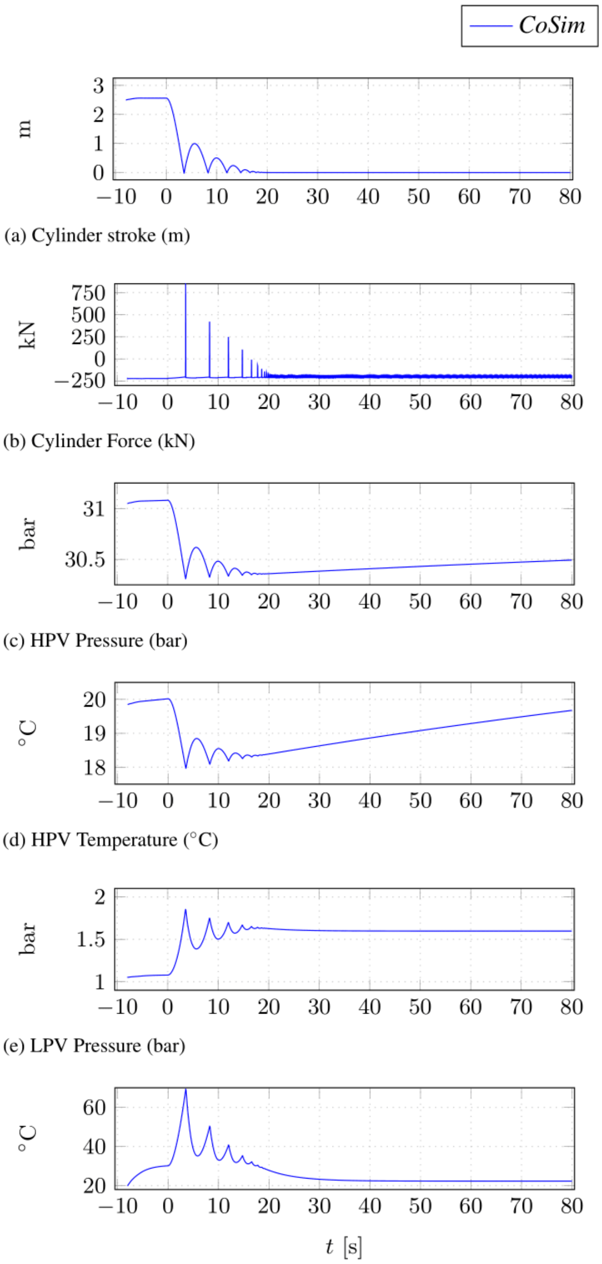

(b) LMRP z-coordinate (m)




(c) Effective tesion at top end of riser (kN)

Figure 6. Basic realistic system response to calm water disconnect (*OrcaFlex* results).

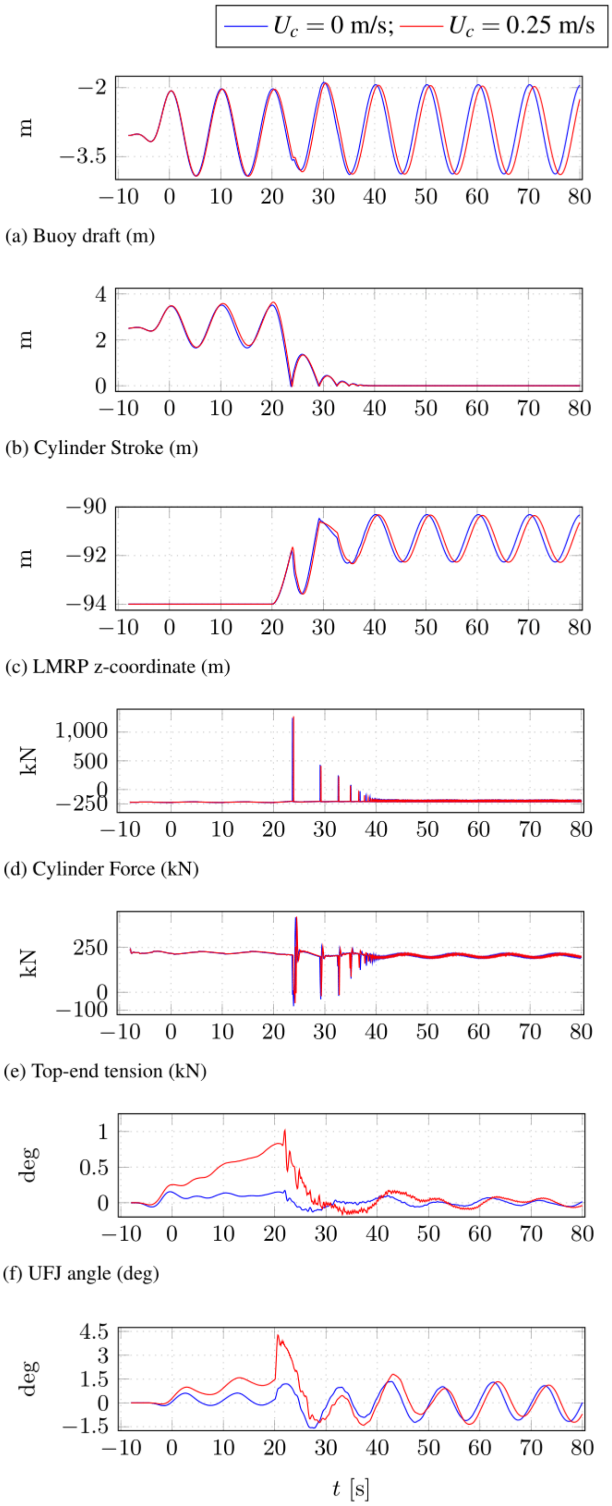
We note that as the piston hits end stroke as indicated in Fig. 7a, momentum is transferred from the riser stack to the platform, as indicated by the peaks inside the red circles in Fig. 6a. The top end of the riser goes into compression as indicated by Fig. 6c during the first hit-of-end-stroke and then attains a value lower than the top end tension in the connected condition. The LMRP response in Fig. 6b reflects this hit of end stroke effect. We also notice from corresponding subfigures of Fig. 7 that, as the piston initially retracts after the disconnect, the HPV pressure drops and the LPV pressure rises, with corresponding reflections in the HPV and LPV temperatures. Since we consider heat transfer effects in the *SimulationX* model, we notice that both the HPV and LPV temperatures tend to attain thermal equilibrium with the surroundings which remain at 20 ℃.




(a) Cylinder stroke (m)
(b) Cylinder Force (kN)
(c) HPV Pressure (bar)
(d) HPV Temperature (°C)
(e) LPV Pressure (bar)
(f) LPV Temperature (°C)

Figure 7. Basic realistic system response to calm water disconnect (SimulationX results).

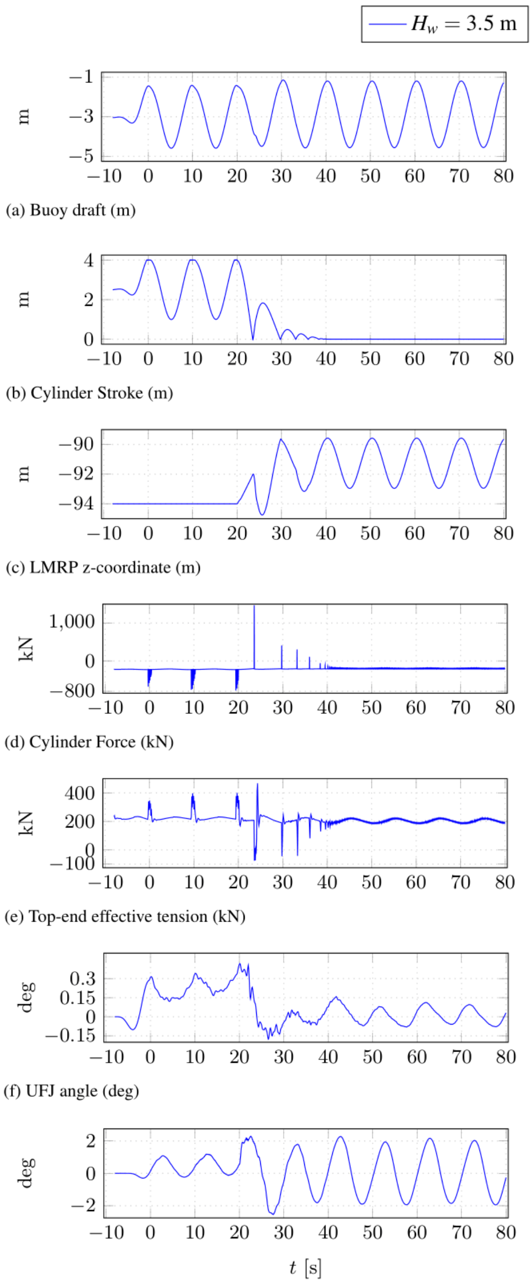
The response of the same system to a disconnect in the presence of waves of height 2 m, wave period 10 s with no current, and a current that varies linearly from 0.25 m/s at the surface to 0 m/s at the seabed is depicted in Fig. 8. Here, the wave and current ramps up in the time interval [−8,0] s, the tensioner is in compensating mode in the time interval [−8,20) s, and the riser is disconnected at $t$ = 20 s. The riser recoils and after few hit-of-end strokes, the piston comes to rest w.r.t. the cylinder. The HPV and LPV temperatures are not plotted owing to space considerations. However, the angles of the upper and lower flex joints are shown.




(a) Buoy draft (m)
(b) Cylinder Stroke (m)
(c) LMRP z-coordinate (m)
(d) Cylinder Force (kN)
(e) Top-end tension (kN)
(f) UFJ angle (deg)
(g) LFJ angle (deg)

Figure 8. Basic realistic system response to disconnect in waves of height 2 m and different conditions of current.

Fig. 9 shows the response of the system in a case where the piston hits the gland end of the cylinder. Here the wave height is $H_w$ = 3.5 m, and there is no current. All other parameters remain the same as in the earlier case.




(a) Buoy draft (m)

(b) Cylinder Stroke (m)

(c) LMRP z-coordinate (m)

(d) Cylinder Force (kN)

(e) Top-end effective tension (kN)

(f) UFJ angle (deg)

(g) LFJ angle (deg)

Figure 9. Basic realistic system response to disconnect with piston hitting gland-end while in compensation mode.

Note the cylinder force as the piston hits the gland end when the buoy rides the wave crest, and the corresponding variations in the crest of the heave plot of the buoy before and after the disconnect.

## V. Conclusion

From the fully coupled simulations of the *basic realistic* system, we conclude that the model successfully captures the interactions between the riser, riser-tensioner, platform, and the mooring system, thus giving the user access to the whole palette of results obtainable from both *OrcaFlex* and *SimulationX*. Further, this also opens up the possibilities to include components that can vary/control the response of the riser-tensioner system, for e.g., the ARV.

The application of the co-simulation methodology presented here readily extends to other areas like wave energy conversion, ship mounted cranes etc., and to all software with API capabilities. It may also be noted that the value of the inertial mass in *SimulationX* may be varied during the course of the simulation, and hence the methodology can be extended to capture the effects of events like mud-shedding etc.

The most prominent drawback of this co-simulation methodology lies in the simulation time. It takes approximately 25 minutes to simulate 80 s of the *basic realistic* system response, compared to the 20 s that a pure *OrcaFlex* linear spring model would take on a workstation with an Intel Xeon CPU E3-1535Mv6 @3.10 GHz, running Windows 10 64-bit OS. However, the range of results made available in both *SimulationX* and *OrcaFlex* justifies the extended duration.

Another drawback is the fluctuation in the top-end tension/cylinder-force results as a consequence of the co-simulation methodology, as observed in Figs. 6c and 7b. However, these fluctuations are noted to be less than 5 % of the top-end tension, and hence is not much of a concern.

Yet another fact to be considered is that the winch wire in OrcaFlex cannot handle compression and hence the present methodology is only applicable in cases where the winch wire is always held in tension.

The next stage of this work envisages the modeling of an in-service riser tensioner system with comparison of simulation results to field data in the case of a planned disconnect. Advanced multiphysical simulation possibilities will also be explored.

## Conflict of Interest

The authors declare no conflict of interest.

## Author Contributions

Savin Viswanathan formulated the cosimulation methodology, carried out the modelling and simulation tasks, analyzed the results and prepared the draft paper. Christian Holden reviewed and verified the simulation results. Olav Egeland formulated the framework of the paper and refined the draft prepared by Savin Viswanathan. The work is an extension of the work done by Ronny Sten [1], who also provided inputs regarding the riser tensioner system. He had also reviewed the models, the results, and the contents of the paper. All authors have approved the contents in the final version of the paper.

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