Numerical Models in Real-Time Hybrid Model Testing of Slender Marine Systems

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Abstract*—This paper presents a study of numerical models used in Real-Time Hybrid Model (ReaTHM) testing, conducted in a still water basin at SINTEF Ocean. ReaTHM testing is a method where a system is divided into physical and numerical substructures to study complex hydrodynamics on the physical system. Basin infrastructure limitations are handled by numerically modeling structural components with large geometrical extent. The numerical and physical substructures are coupled in real-time through a system of sensors and actuators. The emulated system under consideration in the study is a moored axisymmetric cylindrical buoy. The physical substructure is the buoy in model-scale ratio 1:144, while the numerical substructure is the full-scale mooring system consisting of twelve mooring lines. The time scale ratio requires the numerical models to run twelve times faster than real-time. To potentially reduce computational cost, a study is performed of three variations of numerical models, varying from low to high fidelity. The models are evaluated based on the sensitivity to jitter, induced time delays and clock drift imposed on the system.

I. INTRODUCTION

Physical model testing of marine structures is widely used as a mean for the design validation, and for the determination of structural loads and response for varying environmental conditions. The complex hydrodynamics near the free surface, such as slamming, viscous flows, and wave-current interaction, renders it difficult to compute numerically.

Experimental validation is performed through model-scale testing, where the system under interest is scaled with a chosen scale ratio. The physical quantities of the structure and the environmental conditions are scaled accordingly, by using a scaling law such as Froude scaling for inertia dominated regimes and Reynolds scaling for viscous dominated regimes. However, most existing lab infrastructure is insufficient to allow physical tests of larger floating structures such as oil and gas production facilities on deep water of (+1000m), or aquaculture farms in exposed locations at deep water, within a reasonable scale.

To overcome these challenges, hybrid methods have been proposed by [1]–[3], where the structure subjected to complex flow is modeled physically, while the part of the system that does not fit the basin size or scale with a similar ratio, is modeled numerically. The physical and numerical substructures are then coupled in real-time through a sensor-actuator interface, as seen in figure 1.

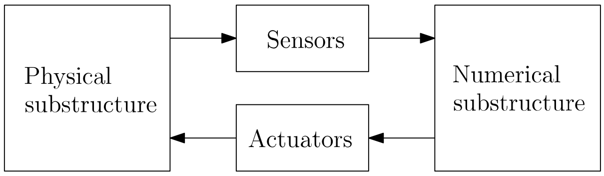

Fig. 1. The physical and numerical substructures are coupled in real-time through a sensor/actuator interface, to simulate the coupled dynamics of the emulated system.

The hybrid testing method has been extensively studied in the seismic engineering community, where the method primarily has been used to decouple nonlinear structural components by using physical models of these and using linear Finite Element Modeling (FEM) to represent the remaining structure [4]. In the application of hybrid methods in seismic engineering, rate dependent phenomena are not necessarily of interest, and long calculation times are in some cases handled by slowing down the time of the physical system, in so-called Pseudo-dynamic testing [4].

For the use in hydrodynamic model testing, the denomination *Real-Time Hybrid Model testing* or *ReaTHM testing*[1] is chosen. ReaTHM testing was first used to numerically model the aerodynamic load on a scale model of an offshore floating wind turbine [5]–[7]. Furthermore, truncation of mooring lines using ReaTHM testing has been studied in [8], [9]

In hydrodynamic model-scale testing, rate dependent behavior from especially waves are of interest, and must therefore be scaled according to the geometric scale ratio. In ReaTHM testing, the numerical models must hence be able to compute a response in "model-scale-time", as time scales with the square root of the length scale ratio following Froude scaling laws. This may prove to be a challenge as ReaTHM tests must satisfy the requirements of reliability and repeatability as good or better than in conventional model testing. High fidelity models for simulation of slender marine systems exist (e.g. RIFLEX [10]), but it may be difficult to make these models simulate faster than real-time simulations.

The objective of the present work is to implement numerical models with different complexity and fidelity as numerical substructures in a ReaTHM test setup. Three different numerical models with varying fidelity/complexity levels

[1]ReaTHM® is a registered trademark of SINTEF Ocean.

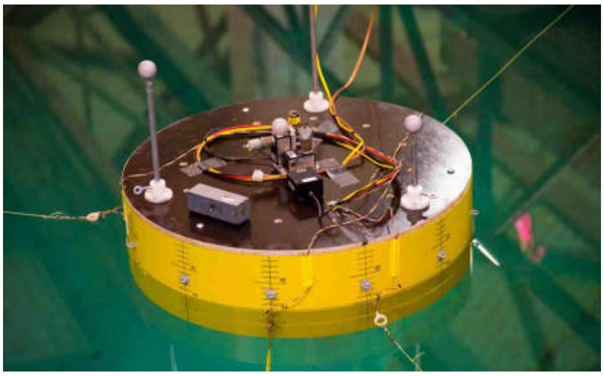

Fig. 2. The physical substructure with attached load cells on the actuation lines, reflective markers for optic position measurement and onboard gyro- and acceleration measurement.

are tested. The emulated system is a floating cylinder buoy, moored with twelve identical mooring lines. The cylinder is modeled physically and the mooring system represented by the numerical models. The occurrence of time delays, induced damping and jitter are measured to compare the performance of the different numerical models. The main scientific contribution in this paper is the evaluation of the feasibility and accuracy of using lower fidelity fast simulation models versus high fidelity FEM code in real-time hybrid model testing.

The study is part of a larger research campaign with an overall aim to develop a real-time hybrid model testing method for both commercial and scientific study of slender marine systems. Development of the real-time system architecture used in the study was presented in [8]. The present paper is outlined as follows, section II describes the numerical models and experimental setup. Section III presents selected results from the study. Section IV discusses the validity of the results, before concluding in Section V.

II. MATERIALS AND METHODS

A. Emulated system

The emulated system in the test was a floating cylinder bouy with a radius of 43.2m and a draft of 14.4m. The floater was moored at a water depth of 320m, with a mooring system consisting of 12 equally spaced identical mooring lines, as exemplified in figure 3. The specification of the mooring line parameters are shown in table I. The division into substructures was performed by placing the physical-numerical interface at the fair-led point for the mooring system. The mooring system is modeled numerically, while the cylinder buoy is modeled physically.

B. Experimental setup

The experimental testing is performed in a still-water basin at SINTEF Ocean. The cylinder buoy is represented physically by a model in scale 1:144. The high scale ratio is chosen for the study to serve as a benchmark test, as increasing the

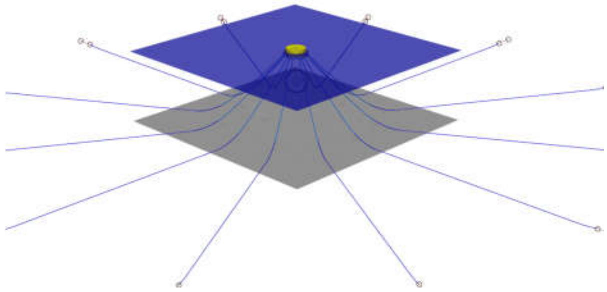

Fig. 3. Visualization of the mooring system, as modeled in RIFLEX.

time scale increase the demands of the numerical models. The model is connected to three rotational actuators in the horizontal plane, with 120 degrees spacing. The actuators apply the force output from the numerical model through a spring and pulley system. The physical model is equipped with an on-board sensor and acquisition system consisting of three accelerometers measuring the linear accelerations in the body-fixed frame, a gyro measuring the rotation rates around the three body-fixed axis and load cells on the actuation lines. The sensor data is sampled at 1200Hz and filtered with an anti-aliasing filter. The filtered data is logged at 300Hz and send to the real-time system at 200Hz. An optical position measurement system is used for real-time tracking of the position in the global reference frame, output as North, East, Down (NED) coordinates with a local reference point. The sensor data from the physical system is used as input for the numerical substructure.

C. Numerical models

Three types of numerical substructures are used in the present work. The models are set up with the parameters given in Table I as input. All models are required to run twelve times faster than real-time, due to the scaling consideration mentioned above. The full-scale time step is set to 0.12 seconds, resulting in the models computing at 100 Hz. The number of degrees of freedom in the models, that is the number of elements per line, are varied to study the convergence of the models. Further, the calculation time is assumed to increase with the number of degrees of freedom, which might introduce jitter/drift and inconsistency of the output.

Linear Isotropic Stiffness: A linear isotropic stiffness model is used as a base case. The model is implemented as a script in the real-time system, which reduces communication time to zero. The stiffness is an ideal linear elastic stiffness, fitted to the tangent stiffness of the mooring system at the equilibrium position. No damping model is included, resulting in zero damping being applied to the physical system. Any damping in the complete coupled system should then originate from hydrodynamic damping affecting the physical body.

FhSim: FhSim is a time domain simulation software developed by SINTEF Ocean, for simulating structures and operations in the fisheries- and aquaculture industry [11]. The

TABLE I
MOORING LINE CHARACTERISTICS AS USED FOR INPUT IN THE NUMERICAL MODELS.

	Length [m]	Diameter [m^2]	C_D-Longitudinal [-]	C_D-Lateral [-]	Mass [kg/m]	Density [kg/m^3]	E-Module
Segment 1	52	0.206	0.37	2.4	262.5	7.80e3	9.22e8
Segment 2	300	0.132	0.37	1.8	73.90	5.39e3	1.23e9
Segment 3	285	0.266	0.37	2.4	436.5	7.80e3	1.23e9
Segment 4	930	0.206	0.37	2.4	262.4	7.80e3	9.22e8

software serves as a platform for several types of numerical analysis, which includes cable models for simulation of mooring systems for aquaculture net cages. The cable model used in the present study was developed by [12], specifically for real-time simulation applications. The theory is based on interconnected rigid bars, with the aim to avoid inversion of the stiffness matrix in each time step, and thus reduce computational time.

RIFLEX: RIFLEX is a non-linear FEM software, developed by SINTEF Ocean for analyzing mooring lines and risers in the oil- and gas industry. The mooring lines are modeled by bar elements, and the mass-, stiffness- and damping matrices are formulated based on the system geometry. Hydrodynamic loads are determined from the generalized Morison equation. In the nonlinear analysis, the dynamic equilibrium equations are solved by stepwise numerical integration using the Newmak-β method. The integration is done with a fixed time step, with Newton-Raphson iterations of the nonlinear mass-, stiffness- and damping matrices for each time step. The most significant nonlinear contributions to the system are the geometric stiffness, the hydrodynamic loading, and the bottom contact. As the iterations will continue until a certain tolerance is reached, the time required for calculation of one time step varies primarily with the rate of change of the stiffness matrix. That is, if large deformations occur fast, i.e. the physical body has a large velocity, the required calculation time for each time step will increase [10], [13].

D. Real-time system

A thorough description of the Real-Time Hybrid Model test setup architecture was presented in [8]. The system consists of a Labview and a Simulink code both compiled on a cRIO compact PC. The Labview code handles the sensor/actuator interface, while the Simulink code includes all observers, predictors, controllers, and communication with the numerical model. Both systems run at 200Hz and are executed in a parallel timed loop structure. The position and accelerations from the sensor readings in the physical system are fused to estimate the global position and velocity. The 6DOF position and velocity are used as input for the numerical model. The force response from the numerical model is output as 3DOF top tensions for each mooring line. Coupling to the physical system is only applied in 2DOF, the North-East component. The resulting horizontal force in the NED frame is found, and an allocation procedure using pseudo inverse matrix operations calculates the desired tension for each of the three actuators. A PID-type controller applies the output tension, through regulation of the actuator position and feedback of the measured force.

E. Time delays

Time delays are critical in the real-time system, as they introduce a non-physical damping which and may lead to instability in the actuation system [14], [15]. Delays are introduced to the system from communication time, processing time, discrete loop time processes and mechanical actuator delay. A polynomial prediction is performed on the estimated position and velocity to compensate for the constant time delays in the system [8]. The number of time steps to predict is found by measuring the time delays in the system through NTP synchronization of all system clocks, and by performing a round circuit of a reference time signal. The effect of the delay from the different numerical models is quantified by measuring the time delay and estimating the influence on the system damping and stiffness parameters.

F. Damping estimation

The effect of the different numerical models on the damping level for the coupled physical and numerical system is estimated by performing decay tests, where the physical buoy is displaced from the equilibrium position and released to decay. A curve fitting method ([16]) is then used, where the equation of motion is normalized, and the linear and quadratic damping is described by coefficients p_1 and p_2.

$$\ddot{x} + p_1\dot{x} + p_2|\dot{x}|\dot{x} + p_3 x = 0 \tag{1}$$

Results from decay tests are used for the estimation, by using the relation.

$$\frac{2}{T_m} log\left(\frac{X_{n-1}}{X_{n+1}}\right) = p_1 + \frac{16X_n}{3T_m}p_2 \tag{2}$$

The peaks of the decay tests are used for fitting a straight line, where the linear damping p_1, is estimated by the crossing of the y-axis, while the quadratic damping p_2 is estimated by the slope of the line. Only the first five peaks are used, as the low amplitudes of the later peaks are prone to introduce noise in the analysis.

III. SELECTED RESULTS

A series of static displacement tests and dynamic decay tests were performed in a still-water basin at SINTEF Ocean. Selected results from the tests are presented here.

A. Applied stiffness

The stiffness applied to the coupled system was measured by performing stepwise pull-out tests of the physical model. Desired and applied forces were logged, along with the excursion distance from the equilibrium point. Results from three tests, using the linear model, FhSim, and RIFLEX with 90 elements per cable are presented in figure 4. The desired forces calculated by the numerical models are presented with the full drawn lines with the measured stiffness applied to the model shown by the dotted markers. There is a good correspondence between the desired and applied stiffness to the model. For small excursion radii, less than 0.5r, the linear stiffness gives a good fit to the complex models. However, when increasing the excursion radius, both the linear stiffness and FhSim deviates from the RIFLEX output.

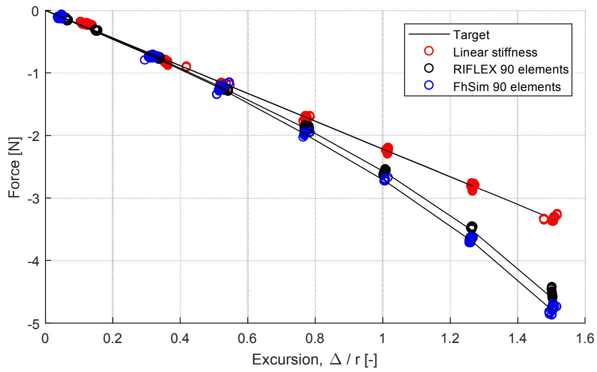

Fig. 4. The target stiffness (full-drawn line) is the output stiffness from the numerical models, dotted markers show the measured applied stiffness, Linear Stiffness (Red), FhSim (Blue), RIFLEX (Black).

B. Dynamics

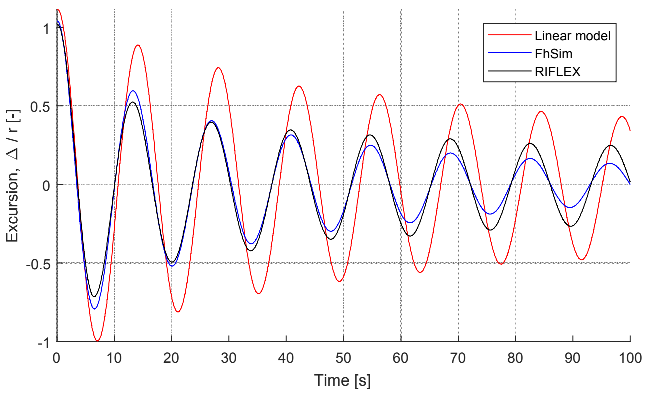

Fig. 5. Decay test, the Liner model (Red), FhSim (Blue) and RIFLEX (Black).

The effect of the numerical models on the dynamics of the complete system was evaluated through performing decay tests. The cylinder buoy was displaced one radius from the equilibrium position and released to decay. The results from

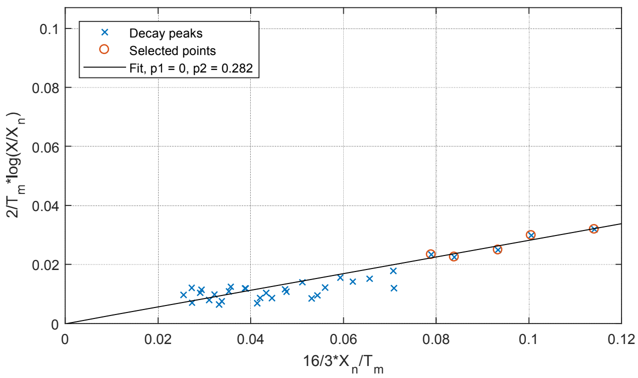

Fig. 6. Damping estimation for the linear stiffness; p_1 = linear damping coefficient, p_2 = quadratic damping coefficient.

decay test with the linear model, FhSim and RIFLEX are shown in figure 5, with the excursion normalized with respect to the cylinder radius.

The natural period of the coupled system is seen to be similar for FhSim and RIFLEX, while the period is slightly longer for the linear model. This is in correspondence with the stiffness being lower in the linear model, for large excursion distances.

Results of the damping estimation for the linear model is seen in figure 6, for FhSim in figure 7 and for RIFLEX in figure 8. The fit for the linear model shows zero linear damping, and a low quadratic damping, compared to FhSim and RIFLEX. The decay peaks fit the line, even for lower amplitudes, although some transfer from quadratic to linear damping occurs. This corresponds with the decay in figure 5, where there is an initial dampening, going towards a standing oscillation, typical for pure quadratic damping.

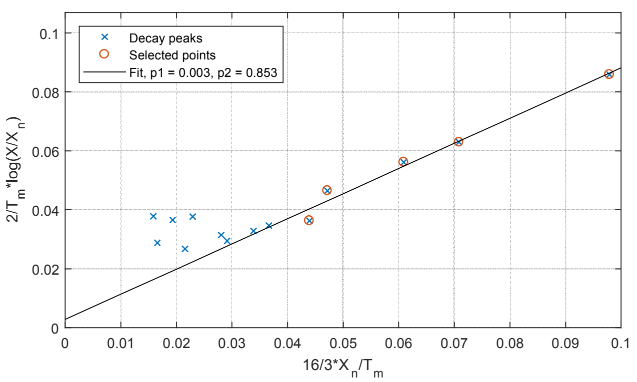

Fig. 7. Damping estimation for FhSim; p_1 = linear damping coefficient, p_2 = quadratic damping coefficient.

For FhSim and RIFLEX, higher quadratic damping terms are observed, indicating that there is a transfer of damping from the simulated mooring lines, onto the physical system.

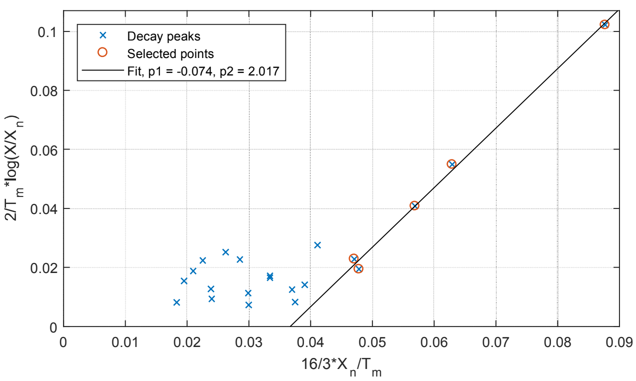

Fig. 8. Damping estimation for RIFLEX; p_1 = linear damping coefficient, p_2 = quadratic damping coefficient.

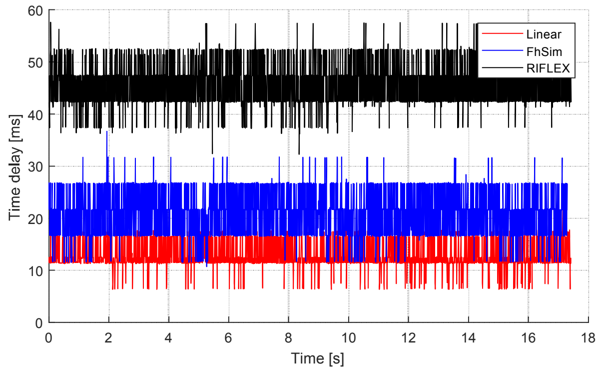

Fig. 10. Measured delay induced by the real-time system plus numerical model. Linear isotropic stiffness(Red), FhSim (Blue), RIFLEX (Black).

The quadratic damping primarily occurs in the first oscillations, after which there is a transcendence towards linear damping. The RIFLEX models show a higher quadratic damping level than the FhSim model, while the following linear damping is highest in the FhSim model.

C. Jitter

Jitter occurs when the required calculation time for a time step is larger than the desired. This results in clock drift, and time lags. The effect of jitter on the output force response is presented in figure 9. The figure shows a segment of a decay test, with a comparison of the force output for a single mooring line, from FhSim and RIFLEX. The linear stiffness does not exhibit jitter, as it is executed directly in the real-time loop. The segment presented in figure 9 was chosen as the floater is released and starts to decay, such that the rate of change of the stiffness matrix is at its maximum.

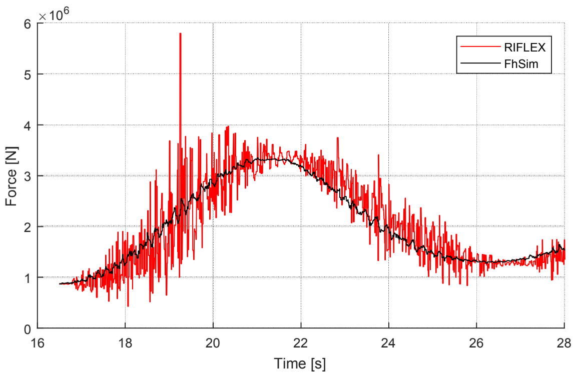

Fig. 9. Output top tension for one mooring line during decay test. FhSim (Black), RIFLEX (Red).

D. Induced delay

Several sources of time delays exist in the system, measurement delay, communication delay and actuator delay. The induced delay from the real-time system is measured as the time from a sample is taken, to an actuator command is sent. The measured delay for a section of a test is presented in figure 10. The delay appears to jitter around a mean value, due to the User Datagram Protocol (UDP) communication. The send and receive loops are not synchronized, meaning that the pure UPD communication time can vary between zero, one and two time steps. From the results the mean value of the time delay using the linear stiffness is approximately 12ms, corresponding to the time delay of the real-time system, for FhSim 17ms and RIFLEX 45ms.

IV. Discussion

This section presents interpretations of the results presented above, and evaluates the validity of the results.

The physical and numerical models were successfully coupled using the Real-Time Hybrid Model testing. The stiffness and damping characteristics from the numerical models were transferred to the measured dynamics of the physical system. However, errors and time delays in the transfer between numerical and physical substructures caused modulation of the system dynamics.

The simplified linear stiffness shows to model the stiffness well near the equilibrium point, while errors are induced by further excursion. A difference was observed between the applied stiffness from the RIFLEX and the FhSim model, as seen in figure 4. The error is assumed to occur, due to the bar elements used in the RIFLEX models have stiffness properties as defined in table I, while the FhSim model uses rigid bars with very high E-module. Further, the difference in quadratic damping and stiffness of FhSim and RIFLEX could be due to different input diameters for the cables.

A time delay on the actuation of the stiffness will induce a negative linear damping component. For the linear stiffness model, the damping ideally originates purely from hydrodynamic damping on the cylinder. The hydrodynamic damping is expected to be quadratic of form, from drag and eddy-making skin friction. At low velocities, the flow becomes laminar and the hydrodynamic damping becomes linear.

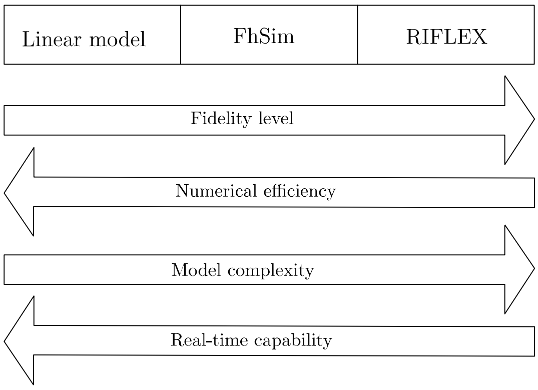

Fig. 11. Choise of numerical model can be made based on requirements for the specific test.

The fact that the cylinder does not decay to rest when the linear model is used, along with the measured time delay of 12ms plus the actuator delay, indicates that negative linear damping has been applied to the system.

A similar time delay was measured for FhSim, which shows approximately the same linear damping for large amplitudes. For lower amplitudes the quadratic damping transcends to linear damping. For the RIFLEX model, the time delay was higher, with an assumed increase in negative linear damping as a result. The results in figure 8 confirms this, as negative linear damping is observed for the fit to large amplitudes.

There is a difference in the occurrence of jitter between the models. FhSim performs well, with low jitter and minor drift during testing, while RIFLEX struggles with performing at 12 times real-time on a regular PC. The high-frequency force spikes, which occur in the RIFLEX output as a consequence of jitter, might not directly impact the dynamics of the tests, as the response frequencies of floating structures are typically much lower. However, the jitter has a large effect on the control system actuating the force onto the physical system, as the force spikes may induce vibrations or even instability. The high-frequency components could be removed through filtering, though this approach would further add time delay to the response.

V. Conclusion

Each of the three models performs well, dependent on which performance criteria is measured. Figure 11 illustrates how different criteria could influence the choice of numerical model. If there is a need for high fidelity or complex models with e.g. bottom interaction, it will be beneficial to use RIFLEX, as the validity is ensured through thorough documentation studies and the general fidelity in nonlinear Finite Element Models. If on the other hand weight is on modeling fast dynamics, with high demand for calculation time, it could be considered to use a faster simplified model.

When planning to use simplified models in real-time hybrid model testing, there is a need for pre-tuning the models offline, to ensure similarity in output from the high and low fidelity models. On the other hand, high fidelity FEM code might need model reduction or computation on large PC clusters, to give smooth outputs for real-time testing.

A solution could be to implement a simplified model directly in the real-time system, by using characteristics of the emulated mooring system obtained through offline simulation, or by online adaption to a simulation model running in parallel.

Acknowledgment

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References

[1] C. T. Stansberg, H. Ormberg, and O. Oritsland, "Challenges in deep water experiments: Hybrid approach," *Journal of Offshore Mechanics and Arctic Engineering*, vol. 124, pp. pp. 90–96, 2002.
[2] Y. Cao and G. Tahchiev, "A study on an active hybrid decomposed mooring system for model testing in ocean basin for offshore platforms," *Proceedings of the ASME 2013 32nd International Conference on Ocean, Offshore and Arctic Engineering OMAE2013*, 2013.
[3] V. Chabaud, S. Steen, and R. Skjetne, "Real-time hybrid testing for marine structures: Challenges and strategies," *Proceedings of the ASME 2013 32nd International Conference on Ocean, Offshore and Arctic Engineering*, 2013.
[4] J. E. Carrion and B. F. Spencer, *Model-based Strategies for Real-time Hybrid Testing*, 2007.
[5] T. Sauder, V. Chabaud, M. Thys, E. Bachynski, and L. Saether, "Real-time hybrid model testing of a braceless semi-submersible wind turbine. part 1: The hybrid approach," *Proceedings of the ASME 2016 35th International Conference on Ocean, Offshore and Arctic Engineering*, 2016.
[6] E. Bachynski, M. Thys, T. Sauder, V. Chabaud, and L. Saether, "Real-time hybrid model testing of a braceless semi-submersible wind turbine. part 1: Experimental results," *Proceedings of the ASME 2016 35th International Conference on Ocean, Offshore and Arctic Engineering*, 2016.
[7] V. Chabaud, *Real-time hybrid model testing of floating wind turbines.* PhD thesis, Norwegian University of Science and Technology., 2016.
[8] S. Vilsen, T. Sauder, and A. Sørensen, "Real-time hybrid model testing of moored floating structures using nonlinear finite element simulations." *the Society of Experimental Mechanics*, 2017.
[9] T. Sauder, A. J. Sørensen, and K. Larsen, "Real-time hybrid model testing of a top tensioned riser: A numerical case study on interface time-delays and truncation ratio." *Proceedings of the ASME 2017 36th International Conference on Ocean, Offshore and Arctic Engineering*, 2017.
[10] MARINTEK, *RIFLEX 4.8.0 User Manual*, 2016.
[11] K. Reite, M. Føre, K. Aarsaether, J. Jensen, P. Rundtop, L. Kyllingstad, P. Endresen, D. Kristiansen, V. Johansen, and A. Fredheim, "Fhsim - time domain simulation of marine systems." *Proceedings of the ASME 2014 33rd International Conference on Offshore Mechanics and Arctic Engineering*, 2014.
[12] V. Johansen, *Modelling of flexible slender systems for real-time simulation and control applications.* PhD thesis, Norwegian University of Science and Technology., 2007.
[13] MARINTEK, *RIFLEX 4.8.0 Theory Manual*, 2016.
[14] T. Horiuchi, M. Nakagawa, M. Sugano, and T. Konno, "Development of a real-time hybrid experimental system with actuator delay compensation," *In Proc. 11th World Conf. Earthquake Engineering*, vol. Paper No. 660, 1996.
[15] M. I. Wallace, J. Sieber, S. A. Nield, D. J. Wagg, and B. Krauskopf, "Stability analysis of real-time dynamuc substructuring using delay differential equation models," *Earthquake Engineering & Structural Dynamics*, vol. 34, no. 15, pp. pp. 1817–1832, 2005.
[16] O. M. Faltinsen, *Sea loads on ships and offshore structures.* Cambridge University Press, 1990, no. 0521458706.