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Development of a Multi-Rate Wave-to-Wire Modelling Tool

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***Abstract*—Transient simulation of full wave energy systems is computationally intensive due to the requirements for hydrodynamics, multibody dynamics and power take-off system aspects, particularly electrical, to be calculated simultaneously. By exploiting the relatively loose coupling between aspects of the PTO simulation and motion calculation in a wave energy converter, a multi-rate solver may be used which takes multiple smaller time steps for some parts of the model in between larger steps for the motion simulation. This paper describes such a system and applies it to a reference wave energy converter model. Initial tests indicate that there are clear advantages to the system in terms of computational efficiency while retaining a high level of fidelity in all model components.**

I. INTRODUCTION

Unlike other power generation technologies, the components of wave energy extraction systems are strongly interdependent in the consideration of the overall performance of the device. In this domain the integrated performance of the hydrodynamic prime mover, the mechanical extraction interface, the electrical power components, control system and control strategy are tightly linked. For instance, a change to the control system of a device, could also necessitate a significant change in the Power Take-Off (PTO) design similarly, a change to the prime mover can impact the required control. The interdependence is stronger than in, say, a wind energy system where a change in the control strategy is unlikely to make a large change to the required generator.

The complex interactions can make full system simulation desirable so designs can be iterated more rapidly, but this presents challenges, not least of which is the computational requirements for producing a high fidelity model of all components. Simulation of the complete system can be computationally very demanding, and execution times excessive, particularly where optimization studies, monte-carlo analysis or real-time simulation is required (for example to implement model predictive control algorithms). The reason for this is that the system usually incorporates some electrical components which should be simulated at a time step significantly shorter than is necessary for the mechanical system and hydrodynamics. Using conventional techniques generally requires that the entire system be solved at the time step of the fastest component. In the case of a WEC, this results in computationally expensive hydrodynamic and multibody dynamics calculations being performed at a much smaller time step than is required for adequate accuracy for that part of the system.

The method described here allows simulation of the PTO, or other subsystems, to be performed at a different rate from the other parts of the system. The PTO behaviour can be solved taking multiple time steps in between the larger time steps used for the hydrodynamics and multibody dynamics. Coupling is achieved via the PTO forces and system positions and velocities which are exchanged at each larger time step. The nested PTO simulation then interpolates the positions and velocities taken in the smaller time steps to generate its results.

In addition, the optimal technique for simulating the system can be quite different for different aspects. For example, the use of an Ordinary Differential Equation (ODE) solving routine might ideally use a non-stiff formulation for the hydrodynamics, but a require a stiff solver for the simulation of the PTO, and the application of the stiff solver to the entire system results in smaller time steps than necessary being taken for all components (increasing computation time). Adding these aspects to the system with a high degree of fidelity can therefore cause simulation time to increase enormously. By partially decoupling the two time steps we can also use a completely different solver if desired to further increase the computation speed.

II. EXISTING TOOLS

The motivation for the development of the tools described in this paper is as part of a project to develop a direct-drive integrated electrical PTO system for WECs with non-mechanical speed enhancement and integrated power electronics capable of providing adaptive control over a wide range of operating regimes. The development of such a PTO necessitates a realistic and efficient simulation of the dynamic wave energy converter system. There are a number of tools available to the wave energy researcher or device developer for analysis of their systems' performance. Proprietary examples include ProteusDS, AquaSim, OrcaFlex, ANSYS-AQWA. Also available is the open source WEC-Sim [1], [2]. These tools have different strengths and weaknesses, but, it is generally the case that both the proprietary and open source tools are focussed on the hydrodynamics and structural mechanics and give somewhat less consideration to the simulation of the PTO mechanism and power export system, which in most cases is the electricity grid. The new model described here integrates previously developed detailed electrical machine simulation tools [3], [4] with a larger system model.

III. MULTI-RATE MODELLING

A. Background

Multi-rate modelling has been investigated previously to reduce simulation of complex systems, however, interest has waned due to the increasing computing power available, and the added complexity and care required in setting up a multi-rate model. Wave energy extraction, with its very large difference in simulation time constants is a prime example of a case where multi-rate simulation can significantly increase overall simulation speed. In [5] two relatively simple multi-rate simulation schemes are proposed where simulation proceeds with two different fixed time steps, one a multiple of the other, but using the same solver. A significant number of recent previous published academic literature on multi-rate simulation is derived from marine propulsion studies [6]–[9] where similar challenges are faced. In all cases some kind of interpolation is required to determine values of the relevant outer simulation quantities in the intermediate time steps of the nested simulation.

B. Interpolation

The interpolation scheme used in this paper is quite simple and similar to that presented in [5]. In the scheme used here, the basic flow is shown in Fig.1. Simulation begins with a set of initial values for both the outer simulation with larger time constant and step size and nested solver. A first step is taken by the outer solver based on the derivatives calculated in the solver initialisation phase. At this time step, the new values of quantities required by the nested solver are determined, in this case the relative velocity and position of the generator stator and translator. An interpolation function is generated from these new values and the previous values. In this case a simple linear interpolation function is generated with the form $y = mx + c$ for each quantity. The nested solver then solves up to the next step using the interpolation function to generate the necessary intermediate values.

Once the nested solver has completed, any quantities from the nested simulation which are required by the outer solver to generate its state derivatives (e.g. forces) are made available. Here we have used a simple scheme where the final value is used as this was found to give good results, however, it should be noted that some smoothing/filtering may be desirable to avoid sharp changes in the nested solver routine quantities propagating in a chaotic way to outer solver. This is a particular issue when control is involved in multiple interacting systems which may amplify errors [7]. The developed code has the capability to provide the full nested solution history for the large time step period after calculation, so adding such smoothing or filtering would be trivial.

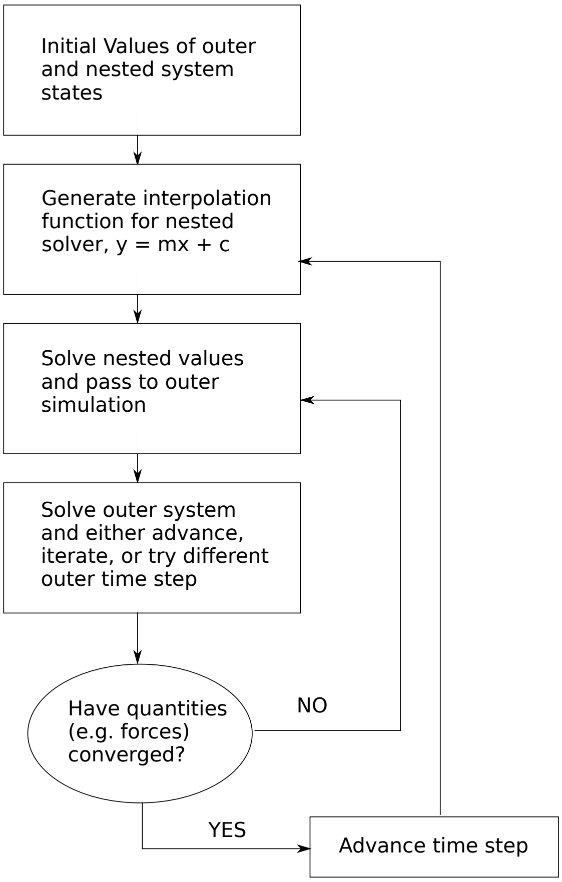

Fig. 1. Multi-rate solver stepping procedure.

IV. HYDRODYNAMIC SYSTEM SIMULATION

In order to test the system concepts developed in the previous sections, it was necessary to create a detailed simulation of a hydrodynamic system with multibody dynamics and integrate it with the multi-rate generator simulation. As discussed previously, a simulation systems exist, however none had sufficient flexibility in their existing configuration to facilitate the integration of the variable rate model. For this reason it was decided to adapt the open-source WEC-Sim code to achieve this. WEC-Sim (Wave Energy Converter SIMulator) is a hydrodynamic and multibody modelling system primarily for the simulation of wave energy converters developed through a collaboration between the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (Sandia). WEC-Sim has the ability to model devices that are comprised of rigid bodies, PTOs, and mooring systems in the time-domain by solving the governing WEC equations of motion in 6 degrees-of-freedom, and is developed in MATLAB and Simulink using the proprietary multibody dynamics solver Simscape Multibody. Details of the hydrodynamic calculation employed by WEC-Sim may be found in [2], but it is a semi-analytical solver based on coefficients determined using a Boundary Element Method code such as WAMIT [10] or Nemo [11]. Both of these solvers are natively supported by WEC-Sim's data import functions.

The existing implementation of the main hydrodynamic forces was integrated tightly with Simulink. To develop the new model, the core hydrodynamic modelling code was extracted from the WEC-Sim Simulink model and converted to a pure Matlab code (which can also therefore run in the open-source Octave [12] system). The WEC-Sim code is class-based for the preprocessing phase, and the new code extends the original preprocessing classes to also perform the transient simulation. In addition a new class for managing the system of hydrodynamic bodies was created (called `hydrosys`) and it is this new class which forms the new main entry point of the code.

A. *Multibody Modelling*

As mentioned previously, the WEC-Sim performs multi-body dynamics simulations using the proprietary Simscape Multibody system [13]. As it was desired to avoid the use of Simulink to gain more control over the simulation process this component was replaced with an alternative multibody modelling library. The code chosen to replace this is MBDyn [14], [15], a free and open source multibody dynamics simulator written in C++. MBDyn is a general purpose multibody dynamics code which features the integrated multidisciplinary simulation of multibody, multiphysics systems, including non-linear mechanics of rigid and flexible bodies (geometrically exact and composite-ready beam and shell finite elements, component mode synthesis elements, lumped elements) subjected to kinematic constraints, along with smart materials, electric networks, active control, hydraulic networks, and essential fixed-wing and rotorcraft aerodynamics. It is being actively developed and used in the aerospace (aircraft, helicopters, tiltrotors, spacecraft), wind energy (wind turbines), automotive (cars, trucks) and mechatronic fields (industrial robots, parallel robots, micro aerial vehicles (MAV)) for the analysis and simulation of the dynamics of complex systems. MBDyn was chosen because of its focus on scientific accuracy (as opposed to speed), its large library of multibody element types, including hydraulic and electric elements, and also its licence which facilitated its integration and modification if required.

To link MBDyn with the hydrodynamic model it was first necessary to create an interface to the C++ code from Matlab. MBDyn provides a client library which communicates with the main MBDyn software via sockets. The new Matlab interface is provided via a mex function which uses advanced techniques to provide access to a C++ object which remains in memory and is wrapped in a Matlab 'classdef' class, which results a natural and clear interface. More details of this class wrapping technique can be found in [16], [17]. The interface allows easy initialisation of the communication between Matlab and MBDyn, the setting of forces at each time step in the simulation and the receipt of positions, velocities and accelerations in Matlab after each solution.

B. *Preprocessing Visualisation Tools*

For any WEC developer the ability to visualise the system as they develop a simulation, and view the resulting motions is a key feature in facilitating the development process. Although plots of results and pure numerical analysis is essential, the ability to visualise the system allows obvious faults in the setup to be identified and rectified much more rapidly. For this reason a suite of visualisation tools were created to easily show the positions of elements in the system. A simple two-element double pendulum model diagram is shown in Fig.2. This shows how an MBDyn system is described, with two massive bodies which are attached to structural nodes for which the kinematics of the problem are calculated, interacting via two joints, a pin joint and hinge. An example visualisation of the same system system using the new pre-processing tools is shown in Fig.3. This visualisation is based on the default cuboid shape for bodies provided by the tools, the length, width and height of which can be set in your Matlab script. If available, an STL (STereoLithography) file of a given body in the system can be used to provide a more realistic representation, as will be demonstrated later in this paper.

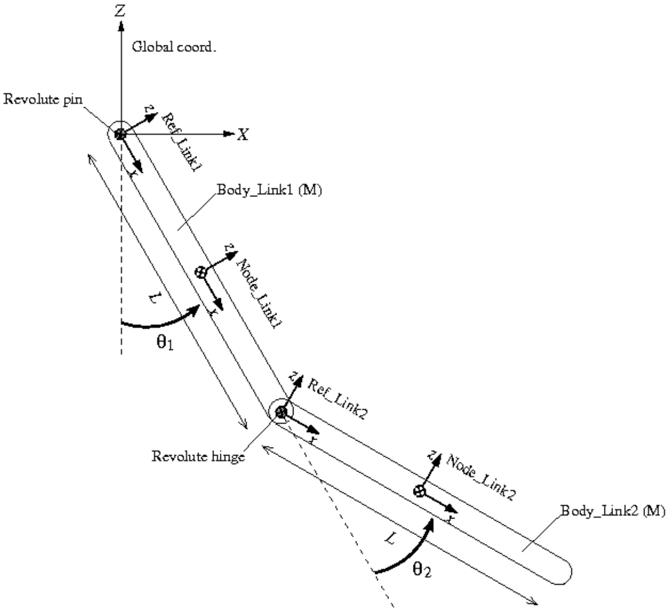

Fig. 2. Diagram showing a simple double pendulum system.

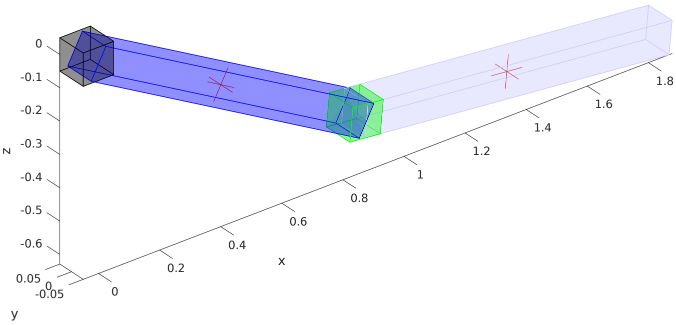

Fig. 3. Visualisation of the double pendulum system shown diagrammatically in Fig 2.

MBDyn makes use of a concept referred to as "References" in determining the location and orientation of components in the system. Placement can be defined relative to other bodies and also other references in a recursive manner meaning the locations of different groups of parts of a model can be easily modified while retaining the relative orientation of other components. As an example, the system in Figs. 2 and 3 may be defined using references such that the initial angle θ_1 may be easily modified while retaining the relative angle θ_2 between the two parts of the pendulum. This concept of references is retained in the Matlab preprocessor and allows complex systems to be created in a modular way.

C. *Postprocessing Visualisation Tools*

To view the resulting motion of the system, several tools are provided though a post-processing class. The class allows visualisation of the trajectories of the nodes in the system, a visualisation at any time step in the simulation, and also an animation of the system motion. An example trajectory plot for the motion of the double pendulum system is shown in Fig. 4. Animations can be viewed or exported to a video file, an example video of the double pendulum system is available at the time of writing online [18].

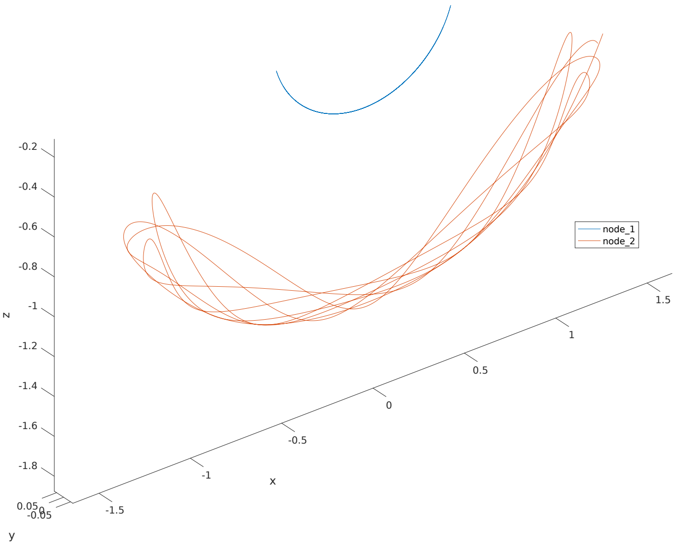

Fig. 4. Visualisation of the example double pendulum system node trajectories.

V. EXAMPLE SYSTEM SIMULATION

While WEC-Sim has been validated by experimental tests, the new code developed here has not. Therefore it is necessary to verify that there are no significant deviations from the original WEC-Sim results. To do so, an example simulation identical to a point absorber example provided by the WEC-Sim authors has been developed. This example is itself based on the RM3 device from the U.S. Department of Energy (DOE) reference model project [19]. The Reference Model Project developed open-source marine hydrokinetic point designs as reference models in order to benchmark technology performance and costs of a variety of wave and tidal energy types, and an open-source methodology for the design and analysis of such technologies. The project was delivered by a group of organisations including the DOE, Sandia National Laboratories, NREL, Pacific Northwest National Laboratory, and Oak Ridge National Laboratory.

TABLE I
FULL SCALE MASS PROPERTIES OF THE RM3 DEVICE.

CG (m)	Mass (tonne)	Moment of Inertia		
Float Full Scale Properties				
0	727.01	20’907’301	0	0
0		0	21’306’091	4305
-0.72		0	4305	37’085’481
Plate Full Scale Properties				
0	878.30	94’419’615	0	0
0		0	94’407’091	217’593
-21.29		0	217’593	28’542’225

The RM3 is a two-body point absorber, consisting of a float and a reaction plate. Full-scale dimensions of the RM3 are shown in Fig. 5 and its mass properties are shown in Table I where the column titled CG is centre of gravity location relative to the mean free surface of the water (X, Y and Z locations respectively moving down the row for each component). It has a PTO consisting of a simple damper acting between the float and spar components which are constrained to move in line with each other (a prismatic type joint). The damping coefficient used is 120 kN/(ms^{-1}) For this example the WEC-Sim authors also chose to restrict the motion to 3 DOF, rotation about an axis parallel to the Y axis and translation in the X and Z directions (this type of constraint is also known as a planar joint), and this has also been replicated. The same system as shown in the MBDyn preprocessor is shown in Fig. 6 (where alternative lighting and solidity options have been used in conjunction with STL files for the bodies to yield a more realistic image).

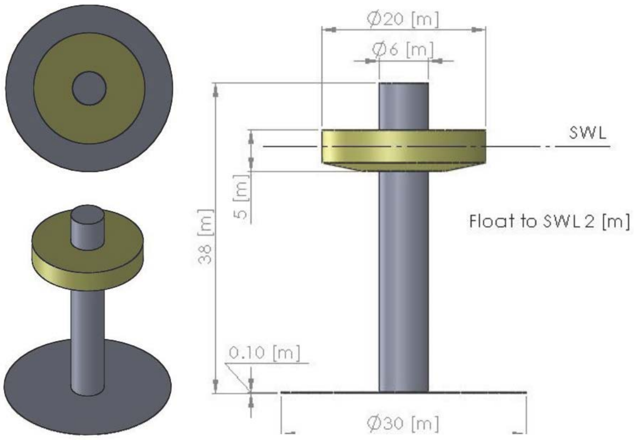

Fig. 5. Geometry of the full scale RM3 example device.

A. *Verification*

To verify that no significant discrepancy has been introduced by porting the hyrdrodynamic calculations to pure Matlab code, and also with the new alternative multibody dynamics

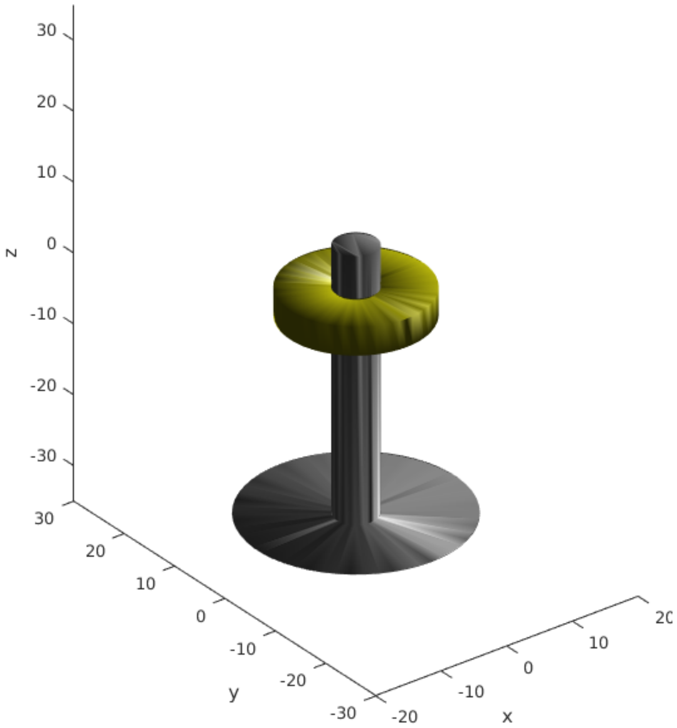

Fig. 6. RM3 example device as shown in MBDyn Matlab preprocessor.

library, identical simulations have been performed with both tools. Incident single-frequency waves of period 8 s and significant wave heigh 2.5 m were applied over 400 s with an initial ramp up in intensity from zero over 100 s. WEC-Sim (and therefore the derived code) has a number of options in how the simulation is performed, in this case the convolution integral method of force calculation was used and body-to-body interaction were activated. Verification was performed in two steps, first the simulation was performed in WEC-Sim, and using the position, velocity and accelerations output by WEC-Sim, the forces were recalculated in the new code and compared to the original. In the second step the new hydrodynamic code was again used, but motion and forces were calculated using the MBDyn based model. Due to the volume of data produced by the simulations a visual comparison in not particularly helpful, and a statistical comparison of the force values has been calculated. The statistics provided are the Root Mean Square Error (RMSE), Maximum absolute error (MAE) and the R^2 correlation coefficient between the data series. The statistics were calculated for all forces and moments for each category combined, i.e. the row 'Body 1 Total Force' refers to the combined data series of forces in all three directions, and moments in all three rotations.

A comparison of the first step, recalculation of forces only, is provided in Table II. It can be seen that there is good agreement with the original and new hydrodynamic forces code with virtually identical results. Note that the 'perfect' correlations of 1.00 are due to rounding to three decimal places. For the second case, with motion calculated by MBDyn the comparison is shown in Table III. It can be seen that there is still good agreement in the two simulation methods, but a small discrepancy is noticeable in the calculation of the hydrostatic restoring force. This requires further investigation, but for the purposes of the study being performed here this agreement is sufficient. The resulting trajectory plot for the nodal motion is shown in Fig. 7. Note that only two of three nodes are visible in the plot, the third node is a clamped reference node placed at the sea bed (-200 m).

TABLE II
STATISTICAL COMPARISON OF ORIGINAL WEC-SIM AND NEW HYDRODYNAMIC FORCE CALCULATION.

Force Description	RMSE	MAE	R2
Body 1 Total Force	22	13	1.00
Body 1 Total Moments	31	15	1.00
Body 1 Excitation Force	3.7e-09	1.7e-09	1.00
Body 1 Excitation Moment	4.5e-10	1.8e-10	1.00
Body 1 Added Mass Force	0	0	1.00
Body 1 Added Mass Moment	0	0	1.00
Body 1 Radiation and Damping Force	22	13	1.00
Body 1 Radiation and Damping Moment	31	15	1.00
Body 1 Hydrostatic Restoring Force	0	0	1.00
Body 1 Hydrostatic Restoring Moment	5e-11	1.2e-11	1.00
Body 2 Total Force	9.4	5.4	1.00
Body 2 Total Moments	11	5.4	1.00
Body 2 Excitation Force	1.7e-09	8e-10	1.00
Body 2 Excitation Moment	9e-11	3.7e-11	1.00
Body 2 Added Mass Force	0	0	1.00
Body 2 Added Mass Moment	0	0	1.00
Body 2 Radiation and Damping Force	9.4	5.4	1.00
Body 2 Radiation and Damping Moment	11	5.4	1.00
Body 2 Hydrostatic Restoring Force	0	0	1.00
Body 2 Hydrostatic Restoring Moment	4.1e-11	9.9e-12	1.00

B. *Integrating Multi-Rate Linear Generator*

With some confidence in the new modelling system established, it was then integrated with the multi-rate PTO simulation. The linear generator simulation requires only the relative position and velocity of its two parts. These can be determined using vector algebra from the three relative position and velocity of the two parts of the WEC. As the WEC components are constrained to move in line with each other, the linear generator is always aligned with the axis corresponding initial vertical (Z) axis of the spar. PTO forces therefore are always applied in this axis in the reference frame of the spar. Given the orientation matrix of the spar in the global reference frame, if the PTO force is denoted F_{pto} and the orientation matrix is $\mathbf{R}$, the force on the two parts of the WEC in the global frame ($\mathbf{F_{gpto}}$) is given by (1) and its negative.

$$\mathbf{F_{gpto}} = \begin{pmatrix} 0 \\ 0 \\ F_{pto} \end{pmatrix} \cdot \mathbf{R} \tag{1}$$

To determine F_{pto} the generator requires the relative displacement and velocity components parallel to the Z axis in the

TABLE III
STATISTICAL COMPARISON OF ORIGINAL AND NEW MODEL WITH MOTION CALCULATED USING MBDYN.

Force Description	RMSE	MAE	R2
Body 1 Total Force	3e+05	1.6e+05	0.94
Body 1 Total Moments	1.4e+05	6.6e+04	1.00
Body 1 Excitation Force	5e-06	2.4e-06	1.00
Body 1 Excitation Moment	1.3e-05	4.9e-06	1.00
Body 1 Added Mass Force	3.6e+03	2e+03	1.00
Body 1 Added Mass Moment	7.3e+03	3.3e+03	1.00
Body 1 Radiation and Damping Force	2.2e+03	1.4e+03	1.00
Body 1 Radiation and Damping Moment	4.2e+03	1.9e+03	1.00
Body 1 Hydrostatic Restoring Force	6.7e+03	3.3e+03	1.00
Body 1 Hydrostatic Restoring Moment	1.4e+05	6.7e+04	0.96
Body 1 Position	0.027	0.014	1.00
Body 1 Angular Position	0.0019	0.00092	0.96
Body 1 Velocity	0.0056	0.0032	1.00
Body 1 Angular Velocity	0.00046	0.00018	1.00
Body 1 Acceleration	0.0043	0.0028	1.00
Body 1 Angular Acceleration	0.00029	0.00013	1.00
Body 2 Total Force	3.2e+05	1.9e+05	0.98
Body 2 Total	1e+05	4.7e+04	0.97
Body 2 Excitation Force	2.5e-06	1.3e-06	1.00
Body 2 Excitation Moment	2.7e-06	1e-06	1.00
Body 2 Added Mass Force	3.1e+03	2e+03	1.00
Body 2 Added Mass Moment	1e+05	4.5e+04	1.00
Body 2 Radiation and Damping Force	9e+02	5.2e+02	1.00
Body 2 Radiation and Damping Moment	1.7e+03	8.1e+02	1.00
Body 2 Hydrostatic Restoring Force	1.2e+02	57	1.00
Body 2 Hydrostatic Restoring Moment	9.8e+04	4.6e+04	0.96
Body 2 Position	0.015	0.0075	1.00
Body 2 Angular Position	0.0019	0.00092	0.96
Body 2 Velocity	0.0045	0.0019	1.00
Body 2 Angular Velocity	0.00046	0.00018	1.00
Body 2 Acceleration	0.0031	0.0015	1.00
Body 2 Angular Acceleration	0.00029	0.00013	1.00

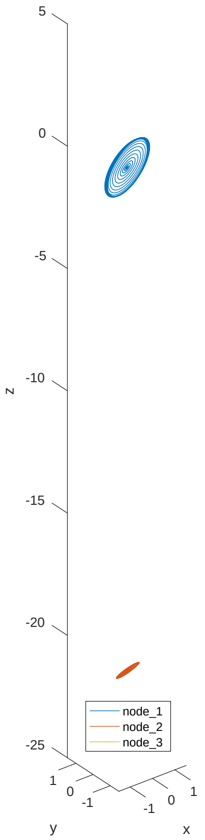

Fig. 7. Trajectory calculated for RM3 test example in MBDyn based simulation system.

reference frame of the spar (or float which will be coincident). The velocity and displacement vectors in this frame can be found by pre-multiplying the vectors in the global frame by the transpose of the spar's orientation matrix. For example, the velocity in the spar reference frame is given by (2) where $\mathbf{v_{gs}}$ is the velocity of the spar in the global frame and $\mathbf{v_{gf}}$ is the velocity of the float in the global frame and $\mathbf{v_{fr}}$ is the velocity of the float relative to the spar in the reference frame of the spar.

$$\mathbf{v_{sr}} = \mathbf{R}^T \cdot (\mathbf{v_{gf}} - \mathbf{v_{gs}}) \tag{2}$$

The relative velocity of the generator parts is then the third component of $\mathbf{v_{sr}}$, and the other components should be zero (to the computing precision of the calculation). The displacement can be found in the same way.

C. Linear generator

The linear generator used is a slotless permanent magnet tubular machine. The specifics of the machine design used here are proprietary as they are a commercial product and therefore cannot be shared. In any case, the design has not been optimised for the RM3 WEC and is significantly undersized. It serves only to demonstrate the practical application of the multi-rate model. More detail on this type of electrical machine can be found in [4], as can details of the modelling methods used to simulate the generator. In the simulation presented here, the generator is connected passively to a resistive load and no control is performed. The generator simulator therefore solves the Ordinary Differential Equation (ODE) shown in (3) where ξ is the generator emf, $\mathbf{R}$ is a vector of phase resistances, $\mathbf{I}$ a vector of phase currents at the current time and $\mathbf{M}$ a 3×3 inductance matrix where the diagonal is the self-inductance of the phases and the off-diagonal terms the mutual inductances between phases. More details of this method may be found in [20].

$$\frac{\mathrm{d}\,\mathbf{I}}{\mathrm{d}\,t} = \mathbf{M}^{-1} \cdot (\xi - \mathbf{R} \cdot \mathbf{I}) \tag{3}$$

This equation was solved in Matlab using `ode15s`, a stiff solver. The performance of non-stiff algorithms (e.g. `ode45`) is poor in this case. MBDyn was used as the 'driver' of the outer solver which uses a fixed-step algorithm, set to use a step size of 0.1 s and a total simulation time of 400 s as in the previous simulations in Section V-A, all other simulation settings were also retained. The use of the convolution integral method to solve the radiation forces precludes a variable step solver in any case. Fig. 8 shows resulting phase currents and velocity profile in the first 200 s of simulation while Fig 9 shows a detailed view of the same waveforms over a smaller time period to demonstrate the level of fidelity that is achieved. As expected the magnitude of the current waveforms follows the profile of the velocity. In this case the outer simulation took a total of 1600 fixed space time steps, while the generator simulation took 75738 variable sized time steps in total to achieve the desired tolerances, i.e. around 21 times as many steps as the outer simulation. Unfortunately the use of MBDyn as the outer solver prevents a direct comparison using `ode15s` to solver the entire system. However, it is very likely that such a system would take even more time steps that the 75738 used to solve the generator equation and the hydrodynamic forces, and motion would necessarily also be solved at every time step.

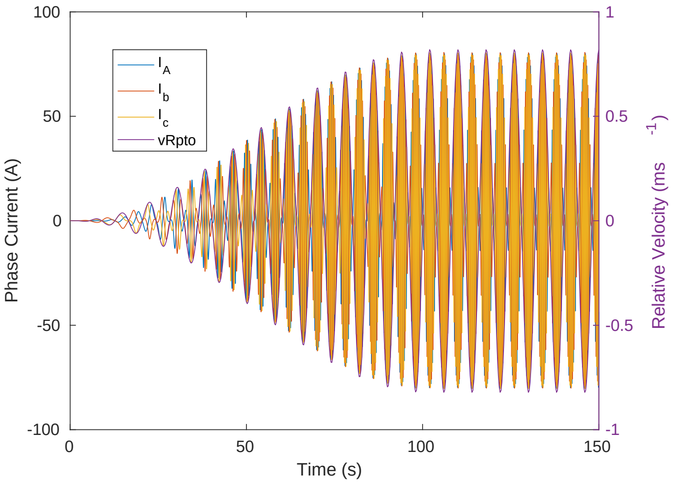

Fig. 8. Detail view of integrated multi-rate simulation output.

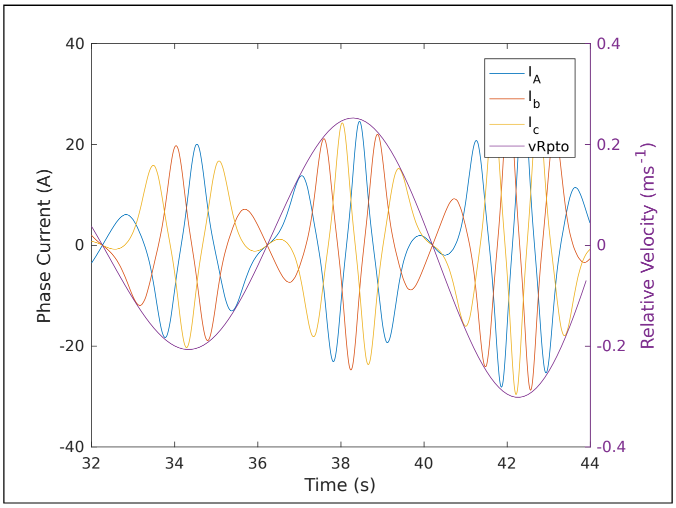

Fig. 9. Detail view of integrated multi-rate simulation output.

VI. Discussion

While more detailed analysis and testing would be required to prove that the multi-rate method retains sufficient accuracy while offering a significant speed improvement, from the basic example seen here the potential for wave energy simulation is clear. Another benefit of this method is the ability to decouple the equation solutions from each other, i.e. if a wave farm simulation was desired, the generators could possibly be solved in separate routines, depending on exactly how they interface to the grid or each other. This would have the benefit that the solution of the system could be more easily be split up and solved on multiple CPUs of compute cluster nodes. It would also mean that slow moving generators (e.g. at the top of bottom of a wave motion) would not have to be solved at the same time step as fast moving generators (e.g. in the middle of a wave motion).

In the cases presented here a fixed step solver is used for the outer simulation, this was most practical as MBDyn only currently supports a fixed step solver, but also because the convolution integral method is used which in the WEC-Sim model is limited to fixed step solvers. WEC-Sim also offers a state-space representation which could theoretically be used with a variable step solver. This is currently being ported to the new system and tested. When a variable step solver is used for the outer simulation, care would be required in choosing a maximum allowed outer time step, otherwise the linear interpolation used for the nested solver could result in distorted flattened velocity profiles and errors would increase. Testing will also therefore be required to prove that the variable step solution with a limit on the step size is still advantageous in comparison to solving the entire system in the same solver. However, some experimentation with other multibody dynamics codes [21], [22] indicates that the stiff solver required by the generator simulation performs very badly, i.e. taking many many more time steps than necessary for a desired accuracy, when applied to the combined multibody dynamics and hydrodynamics problem.

One method of avoiding the maximum step size requirement may be to use an alternative fitting technique such as a cubic spline, over a longer time history of outer steps to create the interpolation function for the nested solver. It is intended that this technique will be applied and tested as development continues.

VII. Conclusions

A combined hydrodynamic and electromechanical simulation of a WEC has been presented with hydrodynamics derived from the open-source WEC-Sim [1] code base and motion calculation performed using MBDyn [14]. This has been combined with a linear generator model which solves at time steps smaller than the main hydrodynamic and motion simulation which has a much larger time constant, and also optimally uses a different ODE solution algorithm. It was found in a basic test that the ratio of generator simulation time steps to outer simulation time steps was 21 indicating that a significant speed up is possible using this technique while retaining a good accuracy. Further testing is necessary to quantify the advantages, but the potential is clear.

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