FloVAWT: Development of a Coupled Dynamics Design Tool for Floating Vertical Axis Wind Turbines

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Introduction & Motivation

The ever-increasing need to curb climate change has led to an increased demand in alternatives to conventional energy sources. Offshore wind energy is one promising alternative energy source as large wind resources may be found offshore. To exploit such resources, wind turbines must be placed in the harsh marine environment, and in many cases, also sited in waters deeper than 50 metres where fixed foundations do not remain economically viable [1].

Whilst floating horizontal axis wind turbines (HAWTs) have been studied for a number of years, floating vertical axis wind turbines (VAWTs) are now gaining interest due a number of advantages over HAWTs for floating applications [2]. To investigate the technical feasibility of such floating systems, it is important to use appropriate engineering models to gain a first insight into their behaviour in the offshore environment.

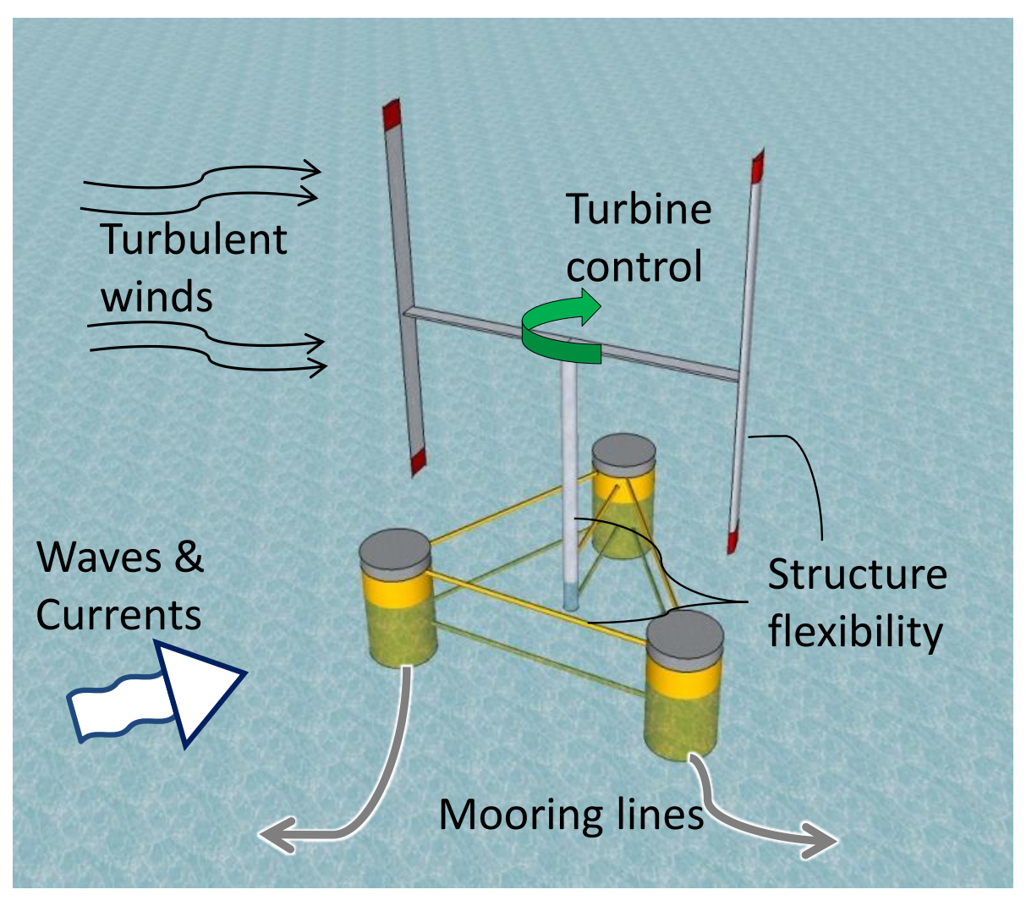

Fig. 1 – Dynamics of a floating VAWT

This involves integrating aerodynamics, hydrodynamics, control dynamics, structural dynamics and mooring line dynamics, that are all present for a floating wind turbine, as illustrated in Figure 1. This work deals with presenting the first attempt to develop a coupled model of dynamics for floating VAWTs, called FloVAWT, with the objectives to perform preliminary assessments of the motion response, system loading and power predictions. The developed model is briefly described, and a case study involving a combined wind-wave energy converter illustrates the capabilities of FloVAWT.

The motivation supporting the development of FloVAWT is the EU FP7-funded H2Ocean project. H2Ocean is aimed at the feasibility study of a multiuse offshore platform, incorporating wind and wave energy, hydrogen fuel production, aquaculture production and biomass [3]. This work illustrates the combined floating VAWT-wave energy converter concept currently being developed in this project.

Coupled Model Development

The first generation of FloVAWT has mainly focussed on interfacing a VAWT aerodynamic model with a hydrodynamic model and including a mooring line model, with the objective to investigate global platform motion, power predictions and characteristics of loads acting on/produced by floating VAWTs in the offshore environment.

The development of such a design tool for the preliminary assessment of floating VAWTs requires the integration of a number of engineering models, usually sourced from other research areas/industries. To overcome typical interfacing problems faced when attempting to couple software packages from different industries, FloVAWT has been developed entirely in the MATLAB/Simulink environment to allow for more robust and efficient interfacing between modules, accelerated model development and easier collaboration between researchers. The visual nature of Simulink also allows for the model to be readily used as a educational tool.

FloVAWT has been developed with the following methodologies in mind:

- Use the same programming language/environment where possible to enable standard interfacing.
- Take a modular approach; reduce models to a number of simpler blocks that can be easily chagnged/verified/validated.
- Where possible, pre-process data to avoid additional computations during simulations to maximise computational efficiency.
- Employ a loose-coupling scheme (allowing for the modular approach), enabling sub-cycling of individual modules to optimise computational efficiency of design tool.

The various engineering models implemented in FloVAWT are briefly illustrated in the following sections below and the process flowchart of FloVAWT is depicted in Figure 2.

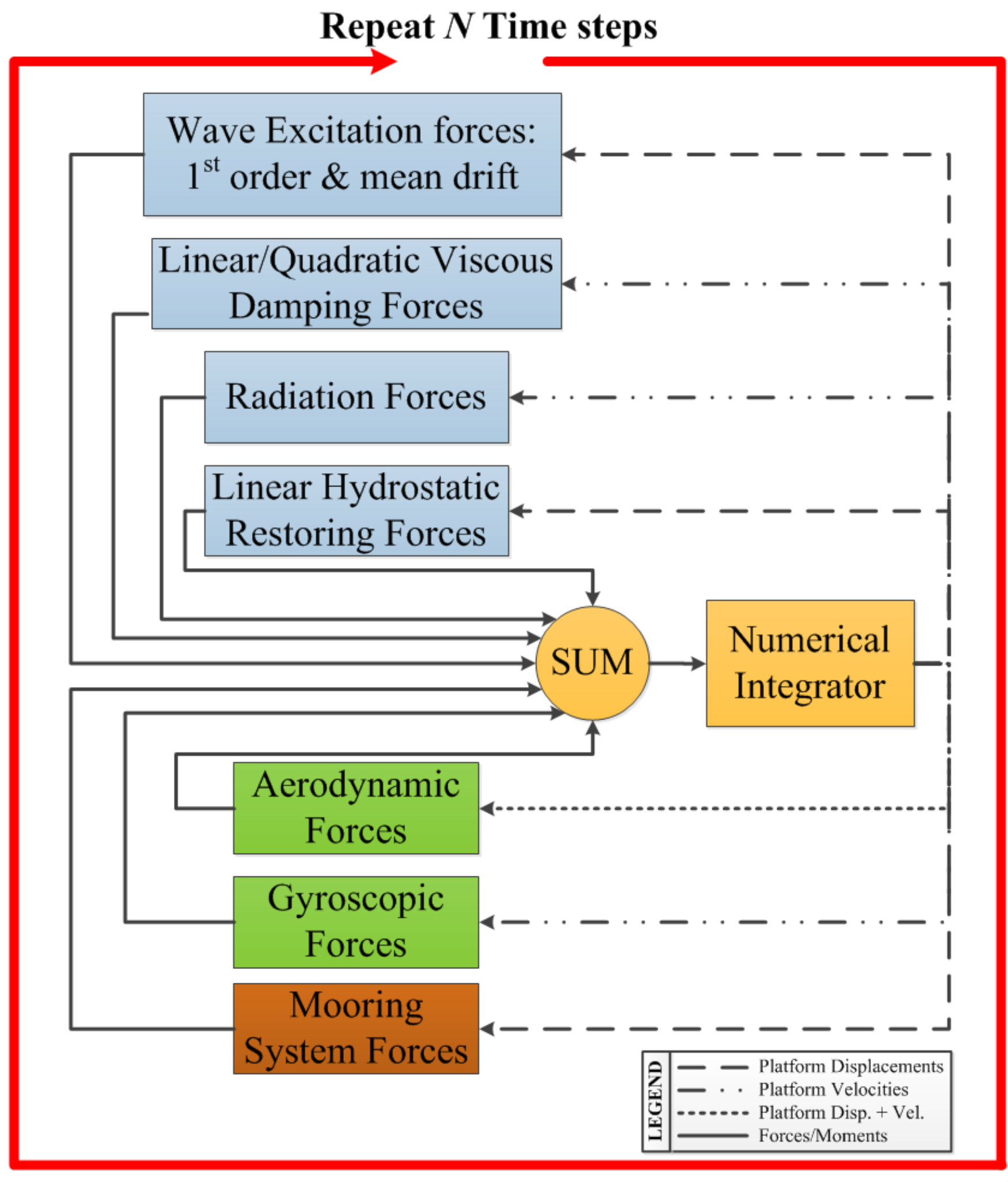

Fig. 2 – Process flowchart of FloVAWT coupled time-domain simulations

Aerodynamics Module

The aerodynamics module is based on the Double Multiple Streamtube momentum model, with several modifications to include dynamic stall (Gormont-Berg) model, tower shadow, tip and junction losses, 3D effects and turbulent incident wind. An alternative vector velocity formulation was implemented to better account for unsteady platform motion. Figure 3 illustrates the module process flow during simulations. Figure 4 provides the validated power curve for the VAWT 260 H-type turbine. Collu et al. [4,5] provides more details on model implementation and validation.

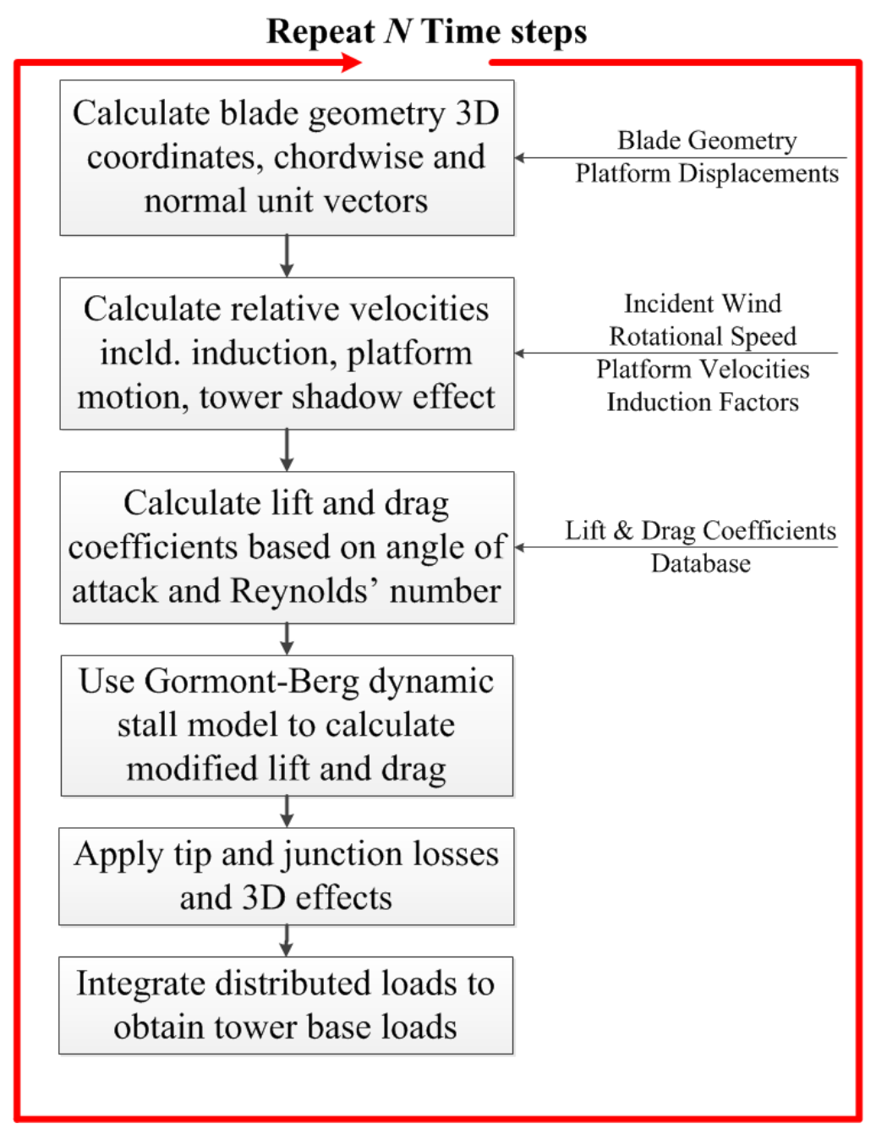

Fig. 3 –Aerodynamic model process flowchart

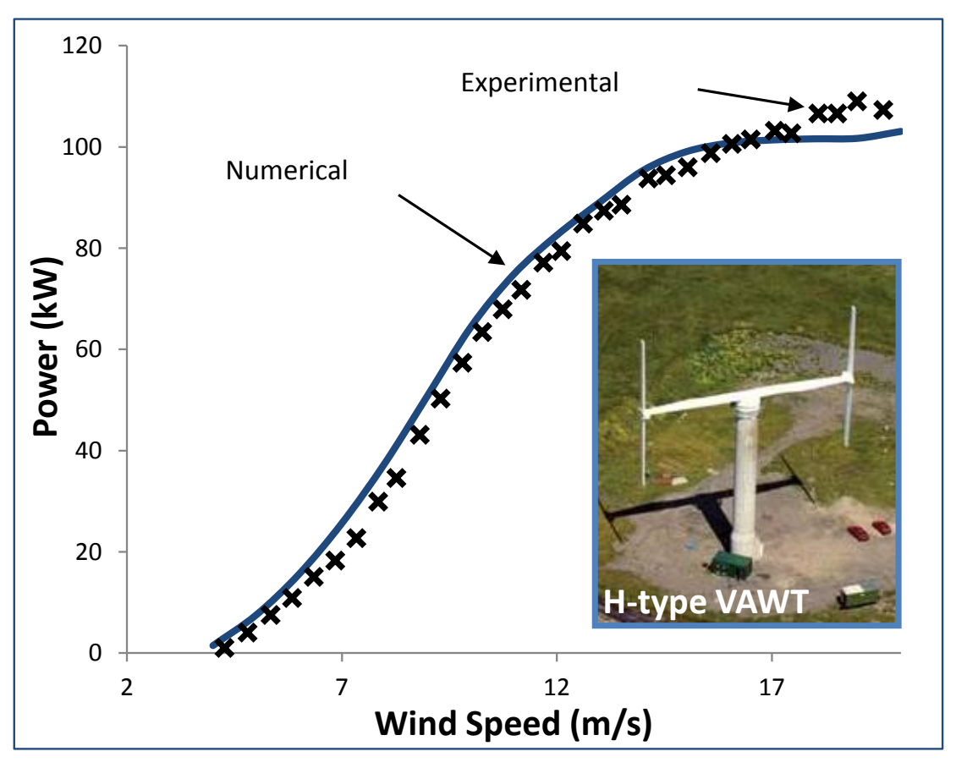

Fig. 4 –Aerodynamic model validation for the H-type VAWT 260 turbine

Hydrodynamics/Inertial Module

The hydrodynamics module is based on the time-domain Cummins equation, with a radiation-force state-space model approximation. The module was constructed using the Marine Systems Simulator Toolbox by Fossen and Perez [6], with a number of modifications and additions relevant to floating VAWTs. Numerical integration of the platform 6 DOF motion is performed in this module. Hydrodynamic aspects considered include:

- 1st order and mean drift wave excitation
- Linear hydrostatic restoring
- Radiation
- Linear/Quadratic global viscous damping

Inertial aspects considered:

- Gyroscopic moments in roll/pitch due to rotating rotor coupled with platform motion
- Time-dependent inertia matrix due to rotating rotor

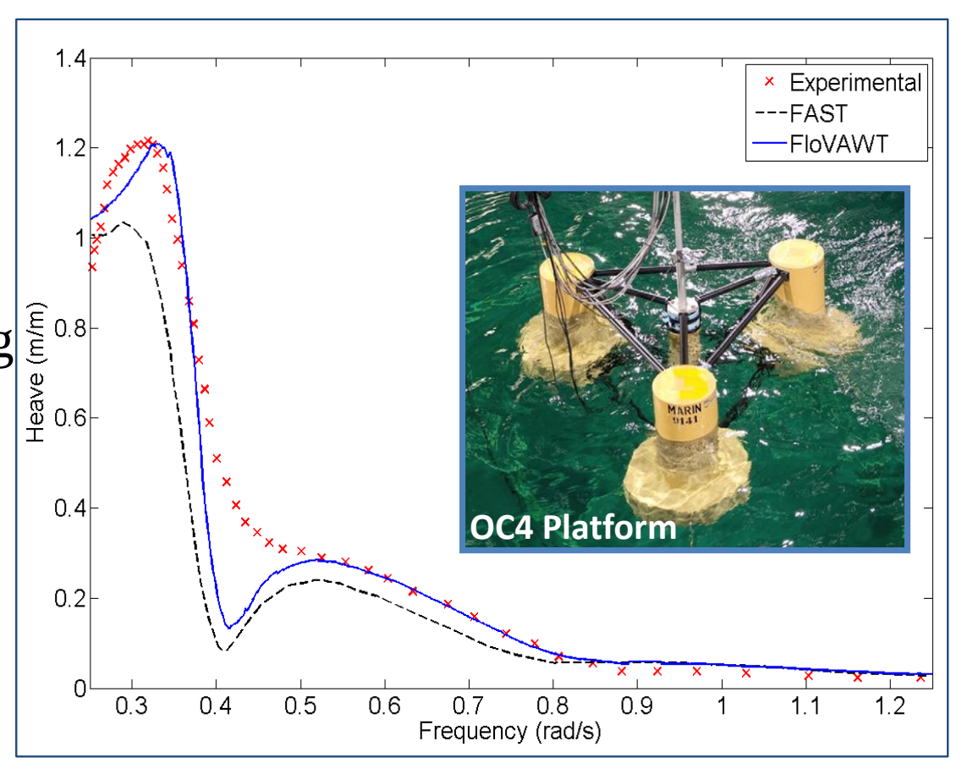

Fig. 5 –OC4 semi-submersible heave RAO predicted by FloVAWT and FAST and experimental data [7] (inset image obtained from [7])

This module has been validated for a number of cases, e.g. GVA4000 semi-submersible and DeepCwind OC4 semi-submersible (see Collu et al. [4,5]). Figure 5 shows validation in heave for the OC4 semi-submersible, also comparing to FAST predictions obtained from Coulling et al. [7].

Mooring Lines Module

The mooring line module is based on the quasi-static approach for catenary moorings and a linearised stiffness matrix for tensioned moorings. In the case of catenary moorings, the model is implemented through a nonlinear force-displacement relation database, which is obtained before running coupled time-domain simulations. The principle of minimum energy is used to solve the quasi-static catenary equations, producing a more robust and computationally efficient formulation, particularly with unconventional mooring designs. Through the use of coordinate system transformations, the platform 6 DOF motion is considered in the 2 DOF quasi-static catenary model. Figure 6 gives an example relation for horizontal (marked *x*) and vertical (marked *y*) fairlead forces of a catenary line as a function of heave and surge platform motion, as calculated by the above-described model.

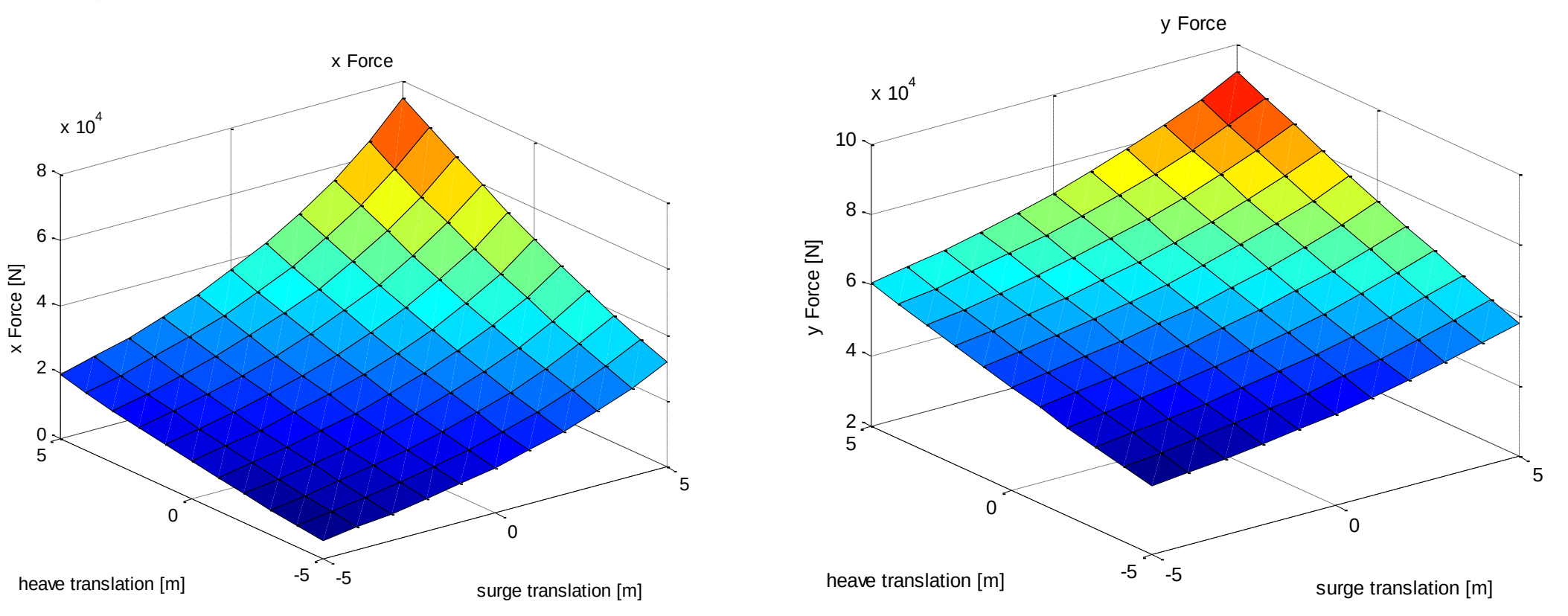

Fig. 6 –Nonlinear horizontal (left) and vertical (right) fairlead forces of a catenary mooring line as a function of heave and surge

Coupled Time-Domain Simulations: Case Study of the H2Ocean Concept

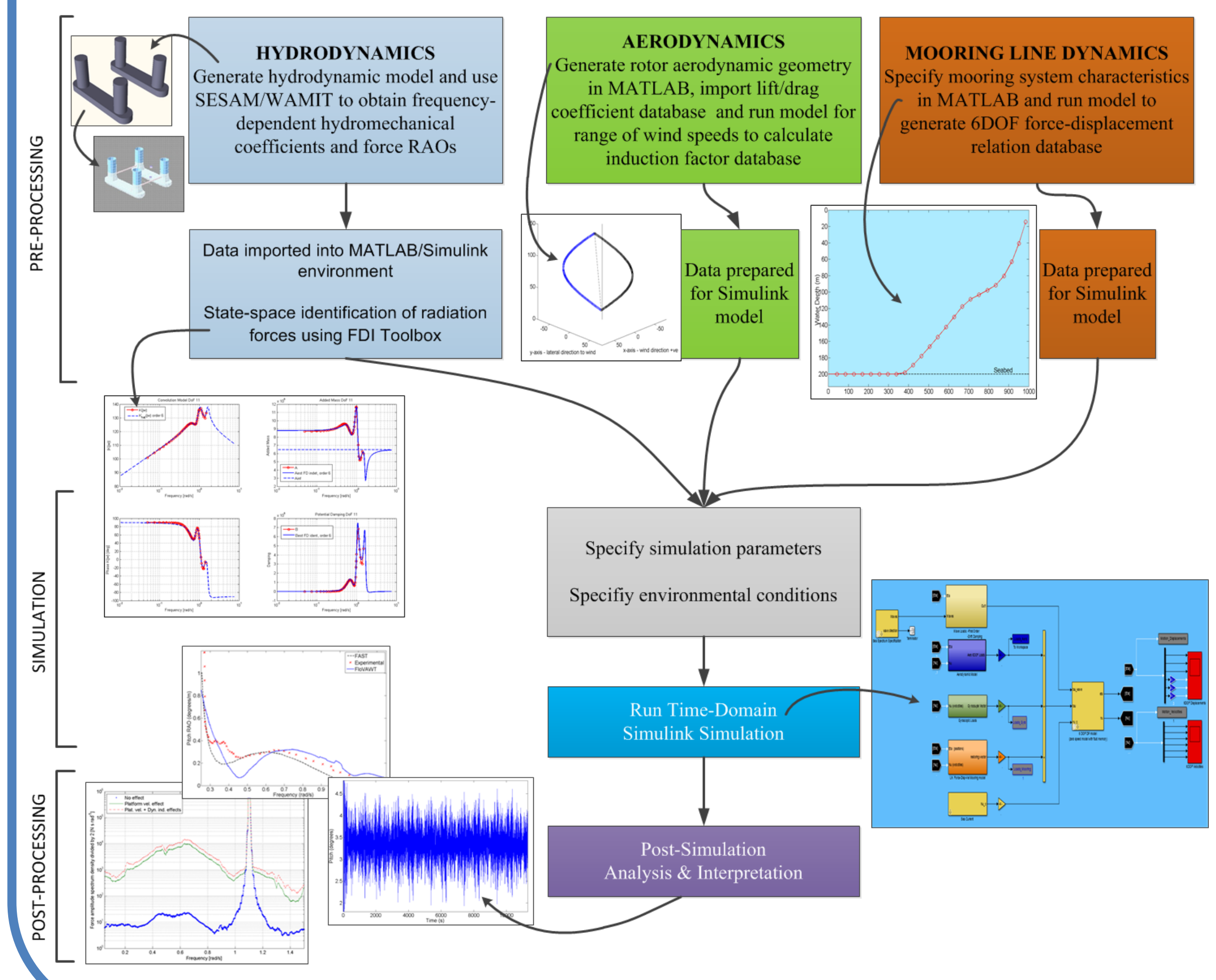

Fig. 7 – FloVAWT model preparation, simulation and analysis process

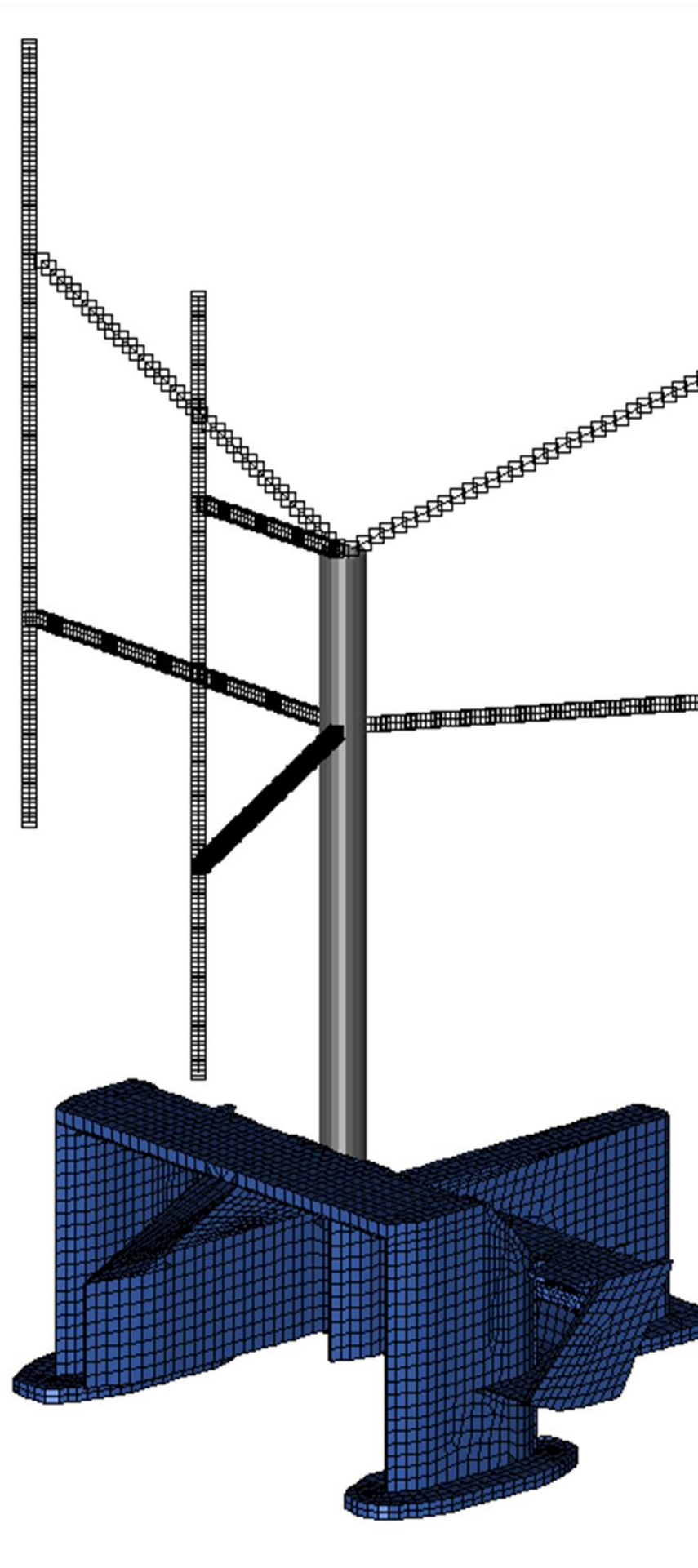

Fig. 8 – Simplified wind-wave energy converter concept

OUTLINE

Figure 7 presents the overall process of preparing and running a FloVAWT numerical model. To demonstrate the capabilities of FloVAWT, a case study was carried out on the combined floating wind-wave energy converter currently being developed in the H2Ocean project. The P80 wave energy converter (WEC) has been developed by Floating Power Plant [8], and is the result of a number of design iterations that have been experimentally tested at different model and prototype scales. The conceptual three-bladed H-type vertical axis wind turbine has been designed by Cranfield University as part of the H2Ocean project. The turbine has a 5MW rated capacity at a wind speed of 12 m/s and 7.5RPM. A simplified illustration of the device is shown in Figure 8.

A number of simulations were run to obtain a preliminary assessment of the performance of this combined wind-wave device, considering met-ocean conditions to investigate the combined dynamics of the device.

COMPUTATIONAL PERFORMANCE

Using a typical desktop PC with an Intel i5-2400 3.1GHz 64-bit processor and 8GB RAM, *simulation ratios of 23:1* were achieved when running the model on a single CPU and with a time step of 0.1 seconds. This efficiency results in many iterative simulations being run over a very short period of time, allowing for engineers and researchers to quickly assess and compare preliminary floating VAWT designs.

RESULTS & DISCUSSION

Figures 9 and 10 present the Amplitude Spectral Densities (ASDs) of the aerodynamic and wave excitation forces/moments in heave and pitch, respectively, for three met-ocean conditions: below-rated (U_{wind}=8m/s), rated (U_{wind}= 12m/s) and above-rated (U_{wind}=25m/s). As can be seen in Figure 10, aerodynamic heave forces are several orders of magnitude (o.o.m) lower than wave excitation forces, as was expected. In pitch, aerodynamic forces are 1 o.o.m lower than wave excitation forces, and in some cases of similar of similar magnitude, particularly around the platform natural frequency, where platform-induced motion augment the VAWT aerodynamic forces. It would be beneficial to further develop the platform and mooring system to shift the platform natural frequencies further away from this frequency range.

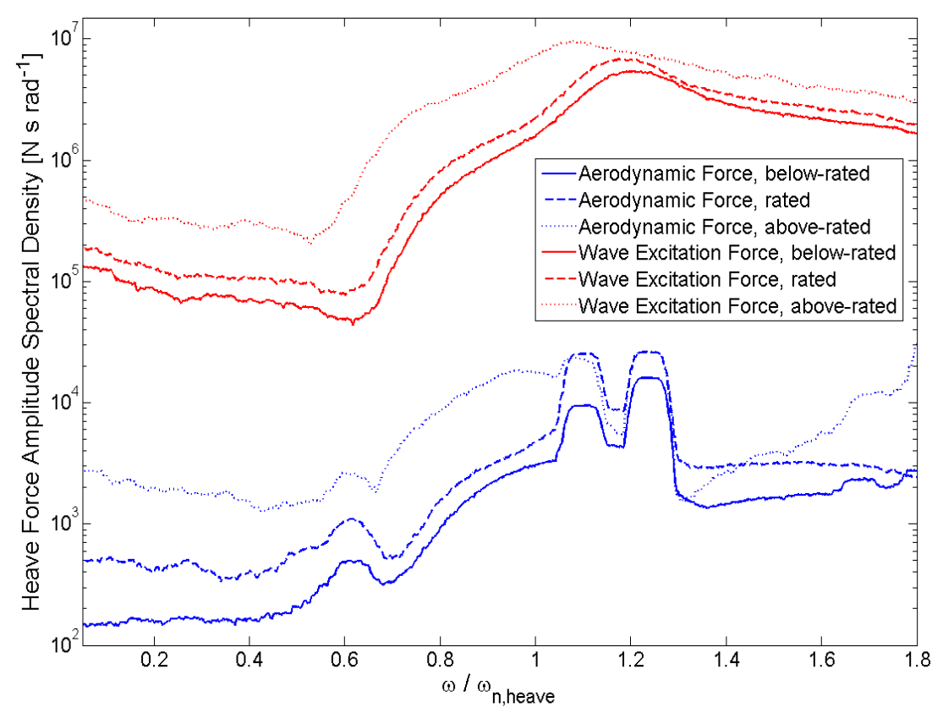

Fig. 9 –H2Ocean concept heave excitation forces

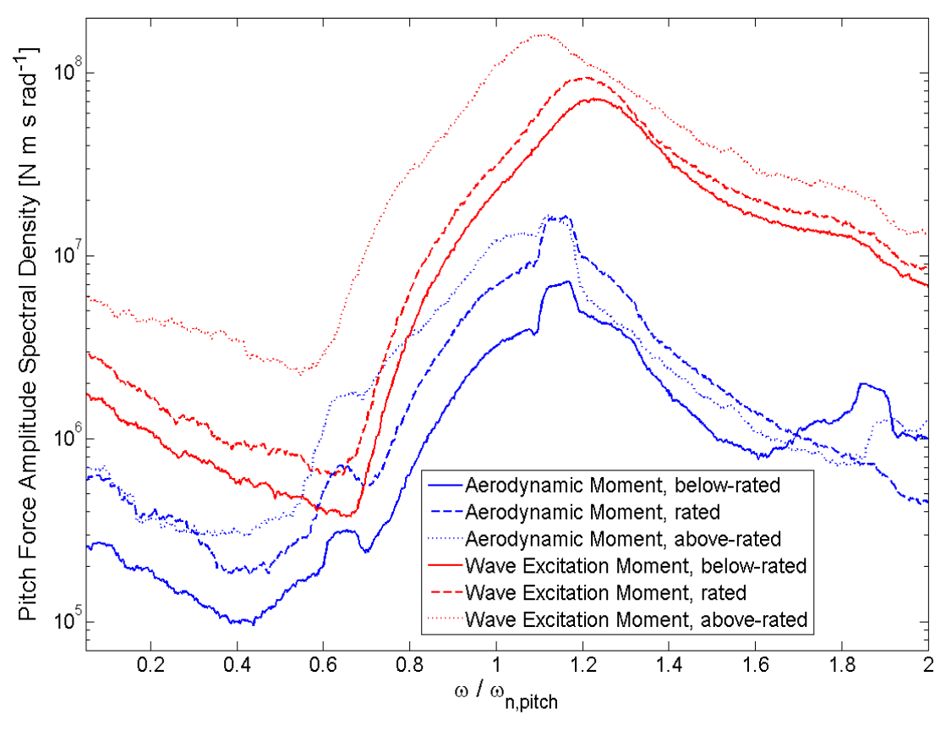

Fig. 10 –H2Ocean concept pitch excitation forces

Conclusions

Need to understand coupled dynamics of floating VAWTs,

Development of efficient coupled aero-hydro-servo-elastic model of dynamics dedicated to floating VAWTs

Approach to coupled model development described,

Description and validation of individual modules presented

Numerical model preparation, simulation and analysis process outlined

H2Ocean concept case study presented

Future Work

The next developments envisaged for FloVAWT are:

- Inclusion of an structural model to investigate internal loading and aeroelasticity
- Inclusion of second-order hydrodynamic forces
- Inclusion of hydroelastic models
- Inclusion of multi-member quadratic hydrodynamic viscous drag model
- Assessment of other aerodynamic models to better capture VAWT dynamics
- Inclusion of a dynamic mooring line model to include hydrodynamic phenomena

References

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Acknowledgements

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COOPERATION

H2Ocean