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INTRODUCTION OF ICE LOADS IN OVERALL SIMULATION OF OFFSHORE WIND TURBINES

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ABSTRACT

Due to the global aim of reducing the CO_2 emissions, renewable energy production comes more and more into focus. Offshore wind energy is one of the most promising technologies especially in northern regions because of the high and constant wind velocities. The challenges among the others are ice loads and especially ice induced vibrations, which are one of the most significant uncertainties in offshore wind turbine design.

Recent investigations in the field of ice mechanics lead to the conclusion that the ice failure has a strong dependency on the dynamic ice-structure interaction. Therefore, a self excited ice structure interaction model by Määttänen-Blenkarn was implemented in a aero-hydro-servo-elastic simulation tool utilizing the state-of-the-art modelling language Modelica. The simulation platform OnWind with a simplified wind turbine model was utilized for simulations. The structural model of an offshore wind turbine consisted of a single wind turbine support structure (tower and vertical monopile substructure) with a representing dead mass on tower top. The implemented ice models were validated by comparing results with existing simulation tools.

The influence of ice velocity on the displacement response in ice-structure interaction was studied by two configurations representing different structural stiffness due to various water depths: 30m ("soft") and 10m ("stiff"). Both configurations were sensitive on frequency lock-in vibration superposed by 1st natural frequency and other frequencies depending on the ice velocity. Vibration of stiffer structure indicated that multiple eigenmodes contributed to lock-in vibration.

It was observed that Määttänen-Blenkarn model was not able to simulate either continuous brittle crushing or intermittent ice crushing. Further investigation should be concentrated to improve the ice load model to describe various ice failure phenomena.

Simulations with OnWind software were carried out successfully creating a promising basis for future research.

INTRODUCTION

The dynamic ice forces and related vibrations of compliant structures under crushing failure have been investigated among others by Määttänen (1999), Kärnä and Turunen (1990), Kärnä et al. (2010) and Yue et al. (2009). Määttänen introduced an ice-induced vibration model based on Blenkarn (1970) and Peyton (1966) studies. Määttänen studied vibration responses for a 90m wide caisson type structure and for a three-legged jacket structure by applying Finite Element Method (FEM) for modal dynamic analyses in time domain. He observed saw-tooth type response at low ice velocity and lock-in vibration at intermediate ice velocity, in which the ice force adapts to the natural frequency of structure. The three-legged jacket structure was observed to be very sensitive for resonant lock-in vibration. Yue et al. (2009) investigated dynamic ice forces and structure vibrations by full-scale tests conducted on a cylindrical compliant monopod platform in Bohai Bay, China. They observed three ice force modes depending on the ice speed: quasi-static, steady-state and random vibrations respectively. These modes are often called in terms of ice crushing respectively as intermittent crushing, lock-in vibration and continuous brittle crushing (ISO (2008)). Same type ice force patterns and structural responses were measured earlier in laboratory tests using natural ice by Kärnä and Turunen (1990).

For wind turbines design and analysis simulation software were used, capable of predicting coupled dynamic loads and response of the system. Offshore wind turbines analyses relies on the use of aero-hydro-servo-elastic codes which incorporate wind-inflow (aero), waves and sea current (hydro), mechanical/electronical actuator (servo) and structural dynamic (elastic) models in the time domain in a coupled simulation software. The OnWind simulation software, developed by Fraunhofer IWES, is a tool which has these features integrated (Strobel et al. (2011)). All components of a wind turbine and environment integrated in this software were modelled using the non-proprietary, object-oriented, equation based language Modelica. This language is originally developed for complex physical systems containing mechanical, electrical, electronic, hydraulic, thermal, control, electric power or process-oriented subcomponents. The language definition is maintained and improved by the Modelica Association. Due to the object orientation of component models of the wind turbine and environment, they can be easily exchanged or extended by using new models.

OBJECTIVES

The aim was to implement a self excited ice structure interaction model into the modelling language Modelica. The simulation platform OnWind with simplified wind turbine model was utilized. The ice was implemented as an additional environmental load model and used to investigate the influence of ice-structure interaction to a single-legged offshore wind turbine. For these investigations ice and structure parameters were varied. Additionally the same ice model was implemented into Abaqus finite element software and the results from both simulations were compared with each other for verification.

NUMERICAL MODEL

Ice load model

Määttänen-Blenkarn model was applied to describe the dynamic load against a narrow vertical structure (Määttänen (1999), Blenkarn (1970)), in which the crushing strength of ice (σ_c) depends both on the relative velocity between the ice and the structure at the waterline as well as the contact area size.

$$\sigma_c = f\left(v - \dot{u}, \sqrt{\frac{A_0}{A}}\right) \tag{1}$$

In Eq. (1) v is the ice velocity and $\dot{u}$ is the velocity of structure at the waterline. The crushing strength of ice is reduced according to the area dependence as defined by Sanderson (1988). The crushing strength dependence on the relative velocity is based on the stress rate as defined by Blenkarn (1970):

$$\dot{\sigma}_c = \left(v - \dot{u}\right)\frac{8\sigma_0}{\pi d} \tag{2}$$

where σ_0 is a reference strength (2 MPa) and d the diameter of the structure. Equation (1) was originally intended for narrow structures. Määttänen (1999) suggested that the applicability for wide structures can be improved by replacing the diameter by one or two times the ice thickness (h_i). In this study two times the ice thickness was utilized.

The rate dependency of crushing strength is given by Määttänen (1999) as

$$\sigma_c = \left(2.00 + 7.80\dot{\sigma} - 18.57\dot{\sigma}^2 + 13.00\dot{\sigma}^3 - 2.91\dot{\sigma}^4\right)\sqrt{\frac{A_0}{A}}\left[MPa\right] \tag{3}$$

in which $\dot{\sigma}$ is given in MPa/s and the reference area A_0=1m^2. The equation is based on the Peyton's measurement data as presented by Blenkarn (1970). Eq. (3) introduces the ice failure mode transition from ductile to brittle. At higher strain rates the ice failure is brittle and strength is assumed to be constant as shown in Fig. 1.

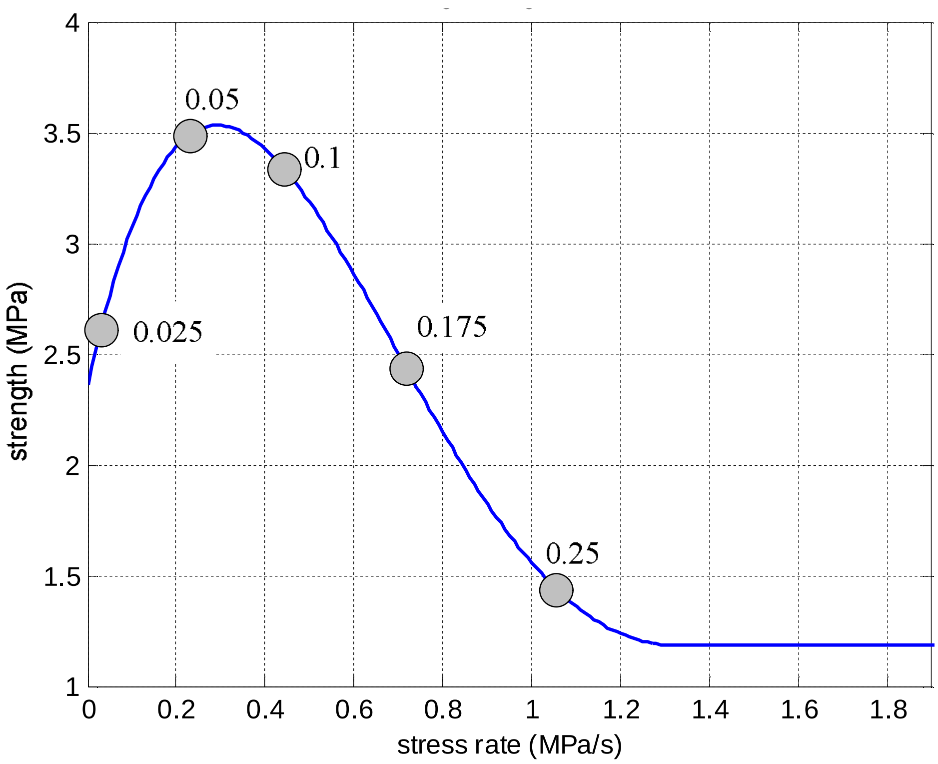

Figure 1. Ice crushing strength as a function of stress rate according to Määttänen-Blenkarn model. Average stress rates in the simulations for different ice velocities are shown by grey dots (the values indicate the ice velocity in m/s).

The dynamic force is determined as follows:

$$F_i = A_i \sigma_c\left(\dot{\sigma}\right) \tag{4}$$

in which the F_i is the nodal force and A_i the corresponding area.

Structure displacement response indicated significant dependency on both, the ice velocity and the stiffness of the structure. Fig. 1 illustrates average compressive strength levels for the selected structure in this study at different ice velocities. Because the contact area of ice is assumed to be constant, the curve is proportional to the ice force. One should observe that when the stress rate becomes negative, i.e., the velocity of the node of the structure at ice level is temporarily higher than the ice velocity, the stress drops to zero. That introduces a gap between the ice and the structure, which closes during following oscillation. This results in sharp force fluctuations which depend much on the stiffness of structure at ice level.

Wind turbine model

The well established NREL offshore 5-MW baseline wind turbine from the Fraunhofer IWES OnWind Modelica library was used for investigations (Strobel *et al.* (2011), Jonkman *et al.* (2009)). The NREL offshore 5-MW baseline wind turbine developed for code comparison purposes is a lifelike three-bladed variable speed 5-MW upwind turbine. In this study, the nacelle, rotor and blades were represented by a dead mass on tower top. This simplification was made to achieve first impression how the self-excited ice load model can be implemented into OnWind simulation platform and to verify the model by comparison to Abaqus FEM-code. An ice-structure interaction analysis with a full wind turbine model is presented by Hetmanczyk *et al.* (2011).

The turbine definition includes aerodynamic and structural data. The main dimensions of the structure are shown in (Table. 1). For more details on the turbine cf. Jonkman et al. (2009). Two different configurations regarding the structure dimensions were chosen to represent different water depths as shown in Fig. 2. For both configurations the hub height is 77.6m, where the mean water level (MWL) for configuration 1 was set to 30m, and for the second configuration to 10m. These configurations represent different dynamic properties and especially different horizontal flexibility at the waterline which have significant influence in dynamic ice-structure interaction. Wide variation in water depths was chosen to emphasize the influence of dynamic properties to ice-induced vibrations. Shape of the structure at the water level is cylindrical with a diameter of 6m.

In both configurations a monopile foundation was fixed at the seabed representing a drill-hole type foundation into bedrock. This corresponds to seabed conditions in a pilot wind turbine installed in the Gulf of Bothnia (Määttänen, 2010). Therefore, soil-structure interaction was not taken into account.

For all flexible structure parts (tower and substructure) a finite element approach based on Euler-Bernoulli beam theory is used. Structural damping was modelled by Rayleigh damping in such way that the Rayleigh coefficients were determined to correspond 1% damping ratio at the lowest natural frequency.

The dynamic analyses with OnWind-platform were carried out by using the mixed explicit/implicit Euler solver. Respectively in Abaqus a direct time integration based on Hilber-Hughes-Taylor algorithm, which is an extension of the Newmark-method, was utilized. The simulation time period was set to 20 seconds.

Table 1. Main dimensions of offshore wind turbine structures with a representing dead mass on tower top.

	Configuration 1		Configuration 2	
	Height	Mass	Height	Mass
Substructure	30.00 m	285000 kg	10.00 m	95000 kg
Tower	77.60 m	228000 kg	77.60 m	228000 kg
Top mass		300000 kg		300000 kg
Sum	107.60 m	813000 kg	87.60 m	623000 kg

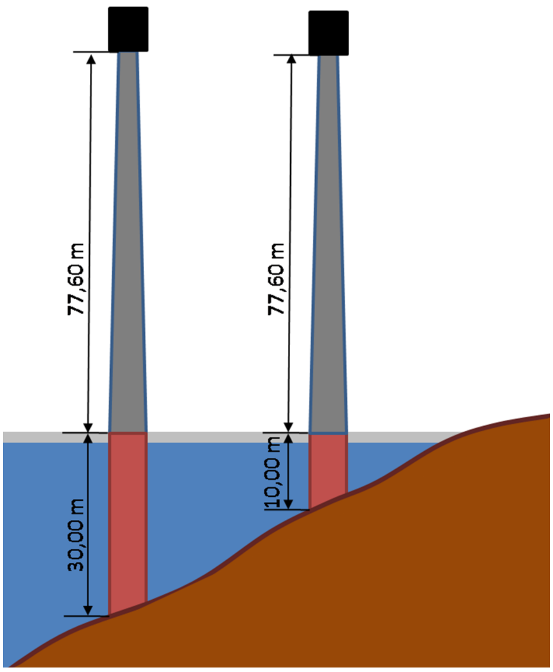

Figure 2. Main dimensions for offshore wind turbine configurations with 30 m MWL (left) and 10 m MWL (right).

The ice model was implemented by creating three different Modelica classes: *model, record* and *connector*. The class *model* contains the ice model with all physical equations as described above. In the class *record* all ice parameters like ice strength and ice velocity are stored and can easily be modified. A class *connector* is developed to connect the ice to the structure. The connector contains a load vector and the structure velocity at ice-structure interaction level. On structure side the model had to be expanded to take ice load into account. Therefore the ice connector must be implemented into substructure elements. After connecting the ice and substructure model the ice load is transformed to nodal loads, which were applied to the finite-element structure model.

Simulation cases

For validation, the ice load model was implemented both into Abaqus finite element software and OnWind simulation platform. The results from both simulations were compared with each other. The comparison was made for both configurations (Table 1).

Investigations of the ice-structure interaction were carried out by varying ice velocity in both structural configurations.

RESULTS

Characteristics of structural dynamic

The dynamic properties for both configurations were determined by the eigenfrequency analysis. Figures 3 and 4 introduce the natural frequencies and mode shapes for the lowest bending type modes.

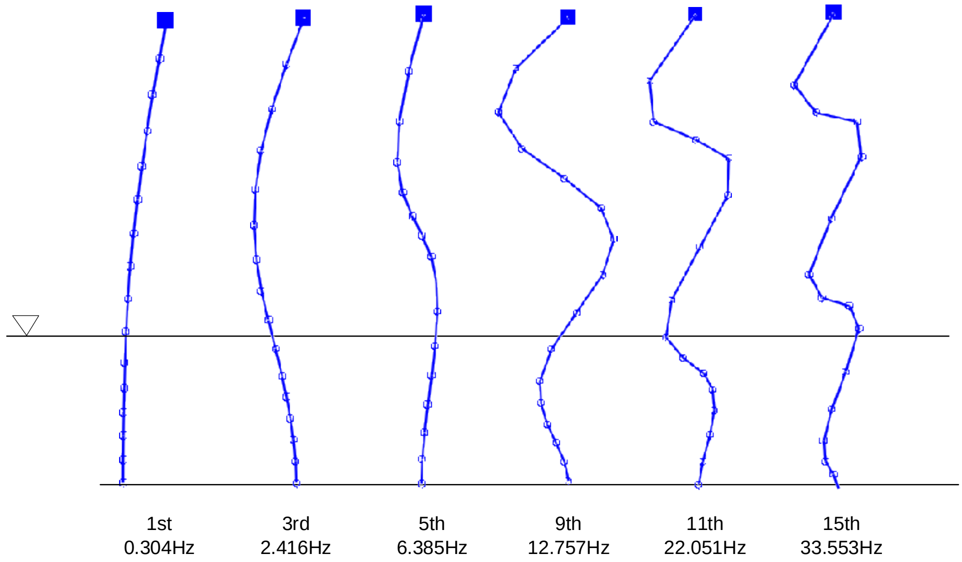

Figure 3. Natural frequencies and mode shapes of 6 lowest bending type modes for Configuration 1 ("soft").

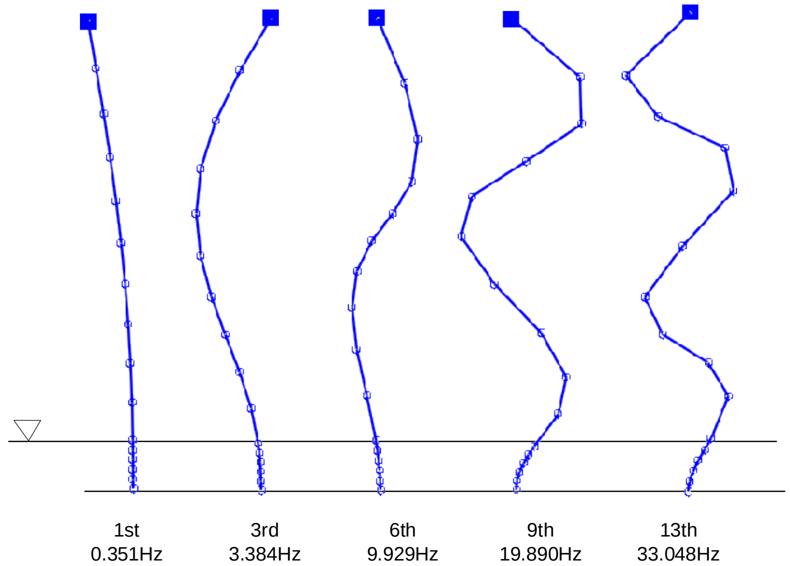

Figure 4. Natural frequencies and mode shapes of 5 lowest bending type modes for Configuration 2 ("stiff").

Model verification

The displacement response from OnWind was compared to Abaqus results to verify the model, as shown in Fig. 5. In the left side the structure displacement at water level for configuration 2 ("stiff") is shown with a MWL of 10 m and in the right picture for configuration 1 ("soft") with a MWL of 30 m. The ice thickness was set to 0.6m whereas the ice velocity was 0.175m/s for configuration 1 and 0.05m/s for configuration 2.

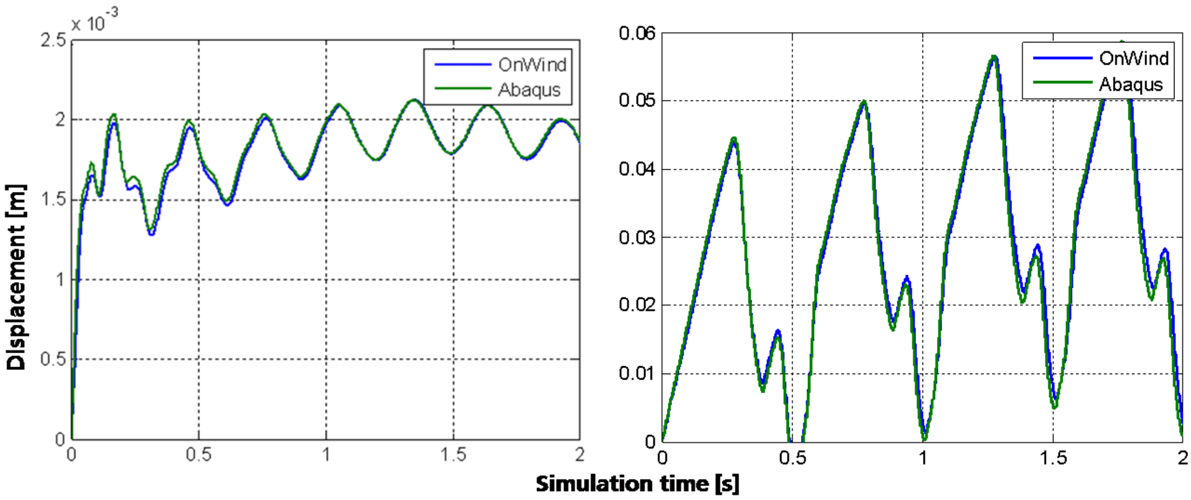

Figure 5. Ice model verification by comparing Modelica (OnWind) and Abaqus: Structure displacement at ice level for reference structure with 10 m MWL (left) and 30 m MWL (right).

A good agreement in the displacement response at ice level was observed for both of the structural configurations. This established a promising basis for further simulations of dynamic ice structure interaction investigation with the overall wind turbine model.

Dynamic ice interaction

The ice velocity has a strong influence on ice-structure interaction due to the velocity dependency of the ice crushing strength (Eq.2). The ice field with an ice thickness of 0.6 m was constantly moving against the wind turbine. The velocity of ice was varied between 0.025 and 0.175 m/s for Configuration 1 ("soft") and respectively between 0.05 and 0.25m/s for Configuration 2 ("stiff"). Time history plot of both configurations are shown in Figures 6 and 7.

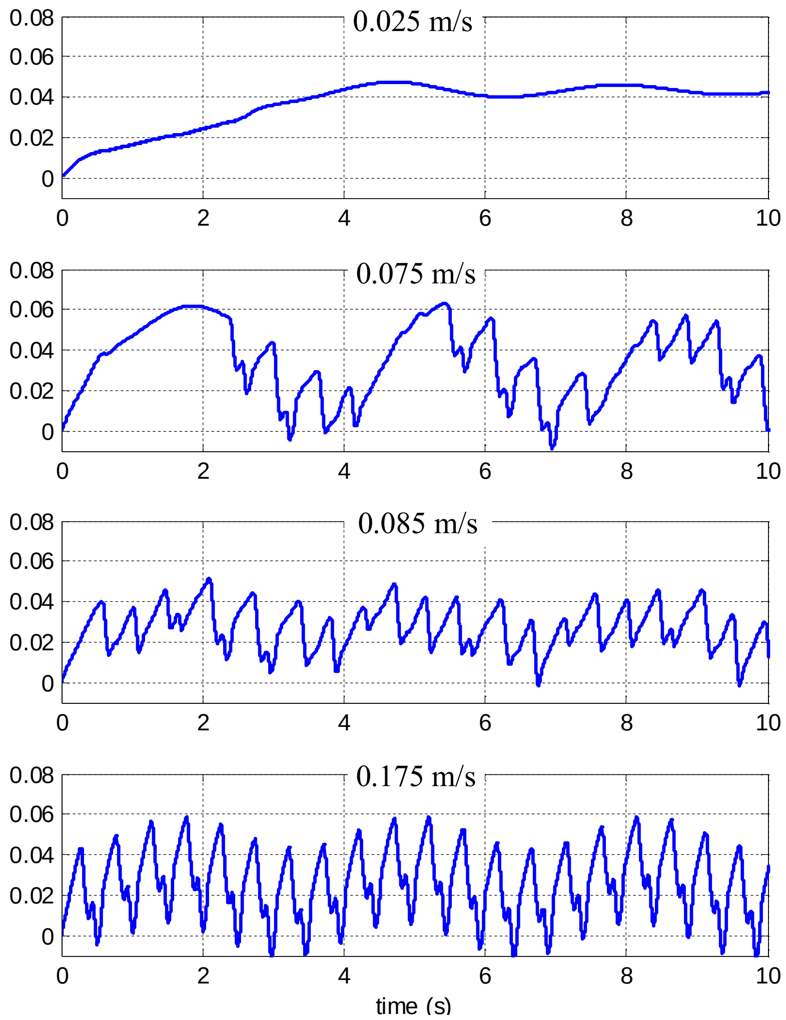

Figure 6. Horizontal displacement response (m) at the ice level in Configuration 1 ("soft"). Different ice velocities are presented ranging from 0.025 to 0.175 m/s.

For the low ice velocity of 0.025m/s the dynamics does not play significant role in Configuration 1 ("soft"). Even though power spectral density (PSD) analysis indicates that the wind turbine starts to vibrate on the first natural frequency of 0.3Hz (see Fig. 8), the displacement amplitude is much smaller compared to other ice velocities. However, the maximum displacement is about the same level than in other velocities due to static displacement. This was interpreted as a ductile type of ice failure.

For ice velocities greater than 0.025m/s fairly similar displacement responses were observed. Saw-tooth like displacement responses were observed with high amplitudes. PSD-analysis indicated that all three cases represent frequency lock-in vibration. For 0.075m/s the 1st eigenmode oscillation dominates the vibration, but also frequency band below 2Hz contributes to the vibration. For the velocity of 0.085m/s dominating frequencies are 0.3Hz (1st eigenmode) and 1.6Hz, which is between 1st and 2nd natural frequency. For an ice velocity of 0.175m/s, a frequency of 1.9 Hz is dominating including contribution from frequencies 0.3Hz (1st eigenmode), 3.8Hz and 5.7Hz.

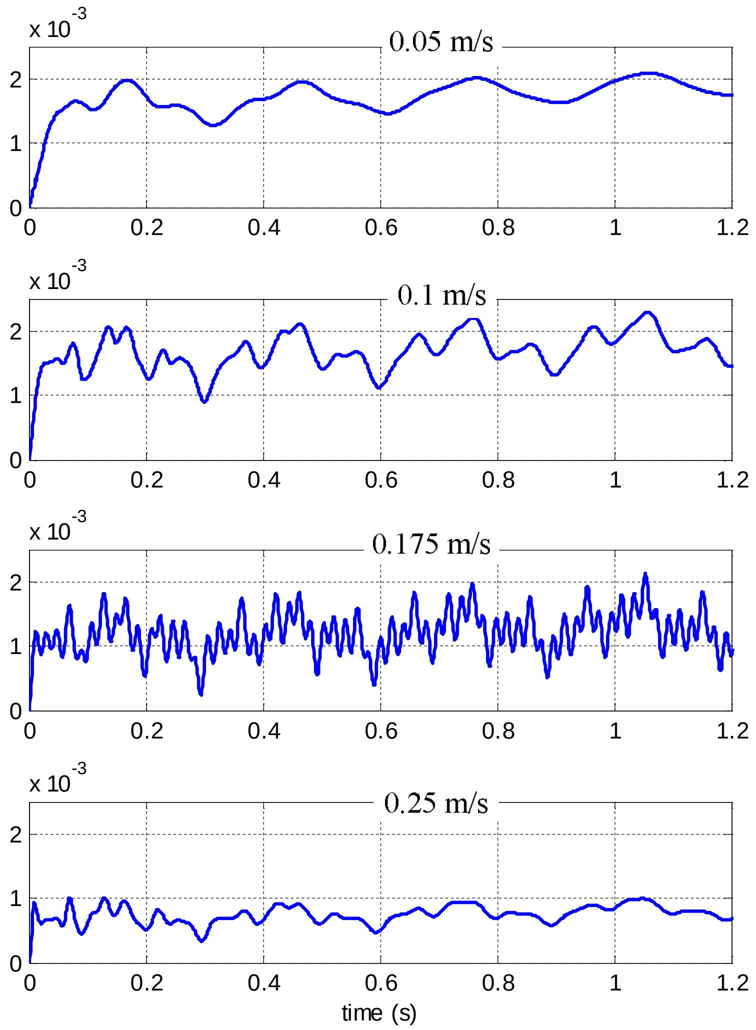

Figure 7. Horizontal displacement response (m) at the ice level in Configuration 2 ("stiff"). Different ice velocities are presented ranging from 0.05 to 0.25 m/s.

Configuration 2 ("stiff") indicated various time signals as shown in Fig. 8. For the visualization purposes a shorter time period is presented than for Configuration 1. Frequency lock-in vibration was clearly observed for all ice velocities within selected velocity range. The 1st (0.35Hz) and 2nd (3.4Hz) mode wake up in all cases, the 3rd mode (9.9Hz) in velocities higher than 0.1m/s and the 4th mode (19.9Hz) wakes up in intermediate velocities of 0.1 and 0.175m/s as seen in Fig. 8. Similar multimodal frequency lock-in vibrations have been reported earlier by Kärnä *et al.* (2010).

Even though Blenkarn-Määttänen model introduces significant dependency between compressive stress and ice velocity in velocity region from 0.1 to 0.175m/s, the displacement amplitudes are fairly similar. Although similar amplitudes and similar PSD-functions, higher velocity (0.175m/s) induced more high frequency oscillations compared to velocity of 0.1m/s indicating a higher risk for fatigue problems. Due to resonant vibration, the velocity of structure at ice level oscillates in a wide range. This leads to a stress rate oscillation over a wide range resulting in large variation of ice strength (see Fig. 1). Because the contact area of ice was assumed to be constant, the ice load is proportional to the ice strength. Therefore, the amplitude of ice load excitation was largest possible within the velocity range mentioned and the displacement amplitude was nearly independent on the ice velocity.

Due to different structural stiffness, the displacements at water level were much smaller in Configuration 2 than in Configuration 1.

For higher velocities (0.25m/s) the displacement amplitudes becomes smaller due to the lower compressive strength and therefore due to lower ice load (see Fig. 1). It was observed in simulations with higher ice velocities that Blenkarn-Määttänen model was not able to introduce continuous brittle crushing. Also, pure intermittent crushing related to slow ice velocities was not observed in any simulations.

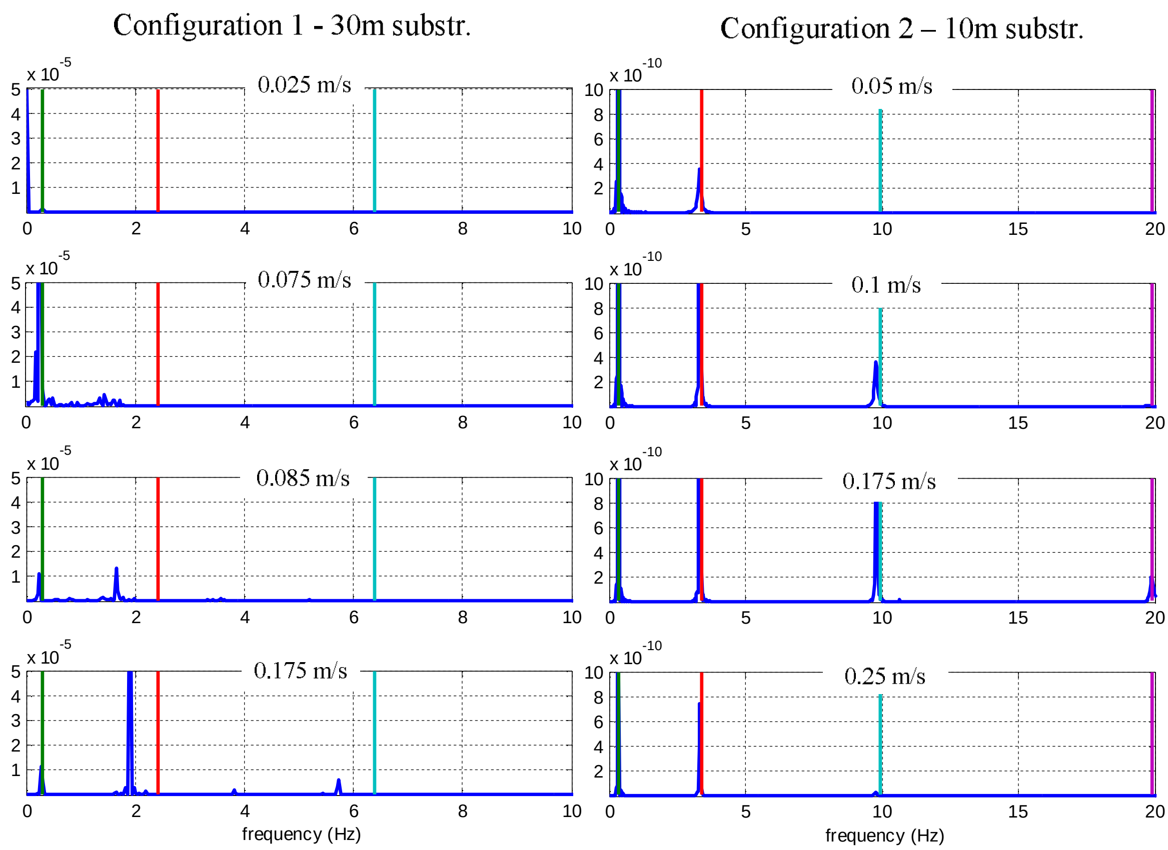

Figure 8. Power spectral density of horizontal displacement (m^2) at the ice level for different ice velocities. Vertical lines correspond to natural frequencies.
Left: Configuration 1. Right: Configuration 2.

CONCLUSIONS

A good agreement was found between the reference ice and structure model implemented in Abaqus and the model implemented with modelling language Modelica and utilizing OnWind simulation software.

Simulations with OnWind software were carried out successfully creating a promising basis for future research. The Määttänen-Blenkarn model was implemented straightforwardly to receive first information about ice-structure interaction in offshore wind turbine simulations. The structural model of an offshore wind turbine was simplified to include a single wind turbine support structure with a representing dead mass on tower top. Ice actions to an overall wind turbine model including a nacelle, rotor and blades was studied in parallel study by Hetmanczyk *et al.* (2011).

The influence of ice velocity on the displacement response in ice-structure interaction was studied by two configurations representing different structural stiffness due to various water depths: 30m ("soft") and 10m ("stiff"). PSD-analysis of time signals indicated frequency lock-in vibration in both configurations. Vibration of Configuration 1 ("soft") was superposed by 1st eigenmode and couple of other non-resonant frequencies depending on the ice velocity. Vibration of Configuration 2 ("stiff") consisted of multimodal displacement response. Within considered ice velocity range between 0.05m/s and 0.25m/s, from two to four of lowest eigenmodes waked up. Higher velocity (0.175m/s) induced more high frequency oscillations compared to velocity of 0.1m/s indicating a higher risk for fatigue problems.

Because Määttänen-Blenkarn model was based on uniaxial compression strength and its dependency on the loading rate, the model has limited capability to describe various ice failure mechanisms. It was observed that the model was not able to simulate either continuous brittle crushing or intermittent ice crushing. Further investigation should be concentrated to improve the ice load model to describe various ice failure phenomena.

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