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FAST Simulations of Drifting Sea Ice Loads on Offshore Wind Turbine Support Structures

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TECHNOLOGY FOR BUSINESS

Abstract

The Baltic Sea features a potential for large capacity wind farms because of relatively high and constant wind velocities. Mostly shallow coastal areas enable cost-efficient foundation and grid connection. However, in the northern sea area - Gulf of Bothnia - the sea freezes annually. Sea ice loads and ice-induced vibrations due to drifting ice field introduce the most significant uncertainties in the support structure design for offshore wind turbines.

The ice load depends on various factors, like the thickness and velocity of the ice as well as the size and shape of the structure. The ice load magnitude and time variation depends on the failure mechanism of ice, which is strongly governed by the shape of the structure at the water level. Sloped shapes like a cone induce the ice to fail by bending as vertical shapes cause the ice to fail by crushing.

A feasibility study of the FAST (Fatigue, Aerodynamics, Structures and Turbulence) simulation software was carried out by investigating the structural performance of offshore wind turbines under coincident ice and wind loads. The results were compared to Finite Element Method (FEM) simulations implemented with an in-house ice load model.

Coupled modelling of ice-structure interaction and wind is a necessary step to improve the accuracy of the ice load evaluation for the cost-efficient structural design.

Objectives

Feasibility study of the FAST simulation software was based on the NREL offshore 5-MW baseline wind turbine with a monopile type of support structure (cf. Jonkman et al. (2009)). FAST is developed by National Renewable Energy Laboratory in the USA for simulating the coupled dynamic response of wind turbines.

Different structural configurations and load cases were studied. Water depths were varied (10 and 20 m) and sea ice parameters were selected to correspond typical ice conditions at Gulf of Bothnia by varying the ice velocity. The ice interaction was studied with vertically shaped structures at the water line (monopile). Both the idling and operation mode were considered and the latter was modelled by a constant wind field with a wind velocity of 10 m/s.

FAST simulations with IceFloe module (version 8) were compared to FEM-simulations in which the OWT (Offshore Wind Turbine) structure was simplified: the nacelle, rotor and blades were represented by a dead mass on tower top. In-house coupled crushing ice load model implemented in Abaqus (version 6.14) software was applied for the validation purposes ((*cf.* Määttänen et al. (1999), Heinonen etal., 2011).

Also, for future development purposes and model validation, some modifications inside IceFloe module were carried out.

Numerical models

Table 1. Model configurations and load cases

	Configuration 1	Configuration 2
Water depth	20 m	10 m
Tower height	77.6 m	77.6 m
Transition piece level	+ 10m	+ 10m
Blade length	63 m	63 m
Structure mass	863 400 kg	768 200 kg
Ice velocity	[0.05, 0.1, 0.15, 0.2, 0.25] m/s	
Wind	[0, 10] m/s laminar	
Natural Frequencies	0.285 Hz 2.405 Hz 6.37 Hz	0.306 Hz 2.88 Hz 7.17 Hz

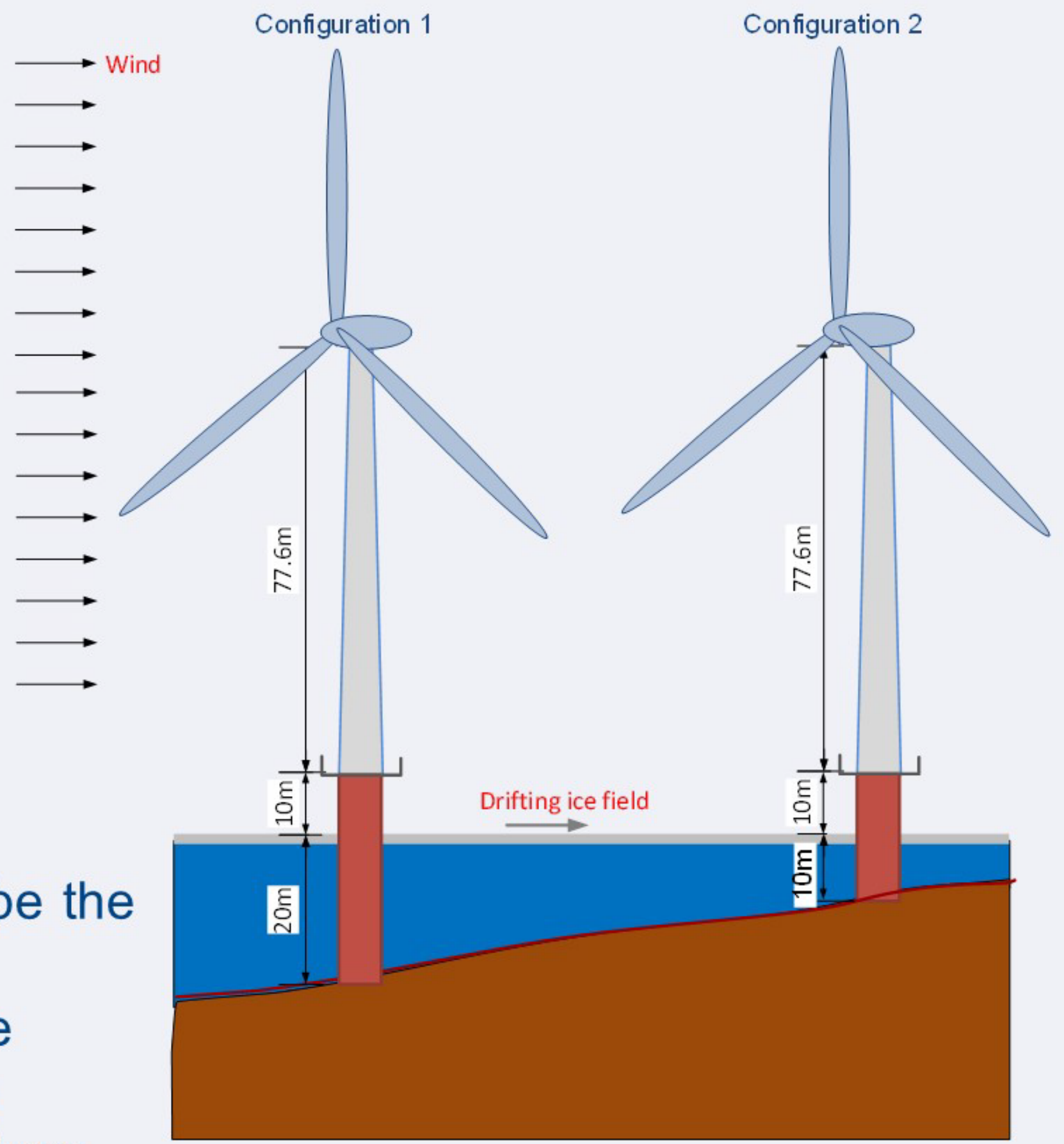

Figure 1. Offshore wind turbine model configurations

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 (v) and the structure ($\dot{u}$) at the waterline as well as the contact area size (A).

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

$$F_i = A_i \sigma_c\left(\dot{\sigma}\right), \qquad \dot{\sigma} = \left(v - \dot{u}\right)\frac{8\sigma_0}{\pi d}$$

in which $\dot{\sigma}$ is given in MPa/s, σ_0 is a reference strength (2 MPa), *d* the diameter of the structure, A_0=1m^2 the reference area, F_i the nodal force and A_i the ice contact area

The model 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. 2.

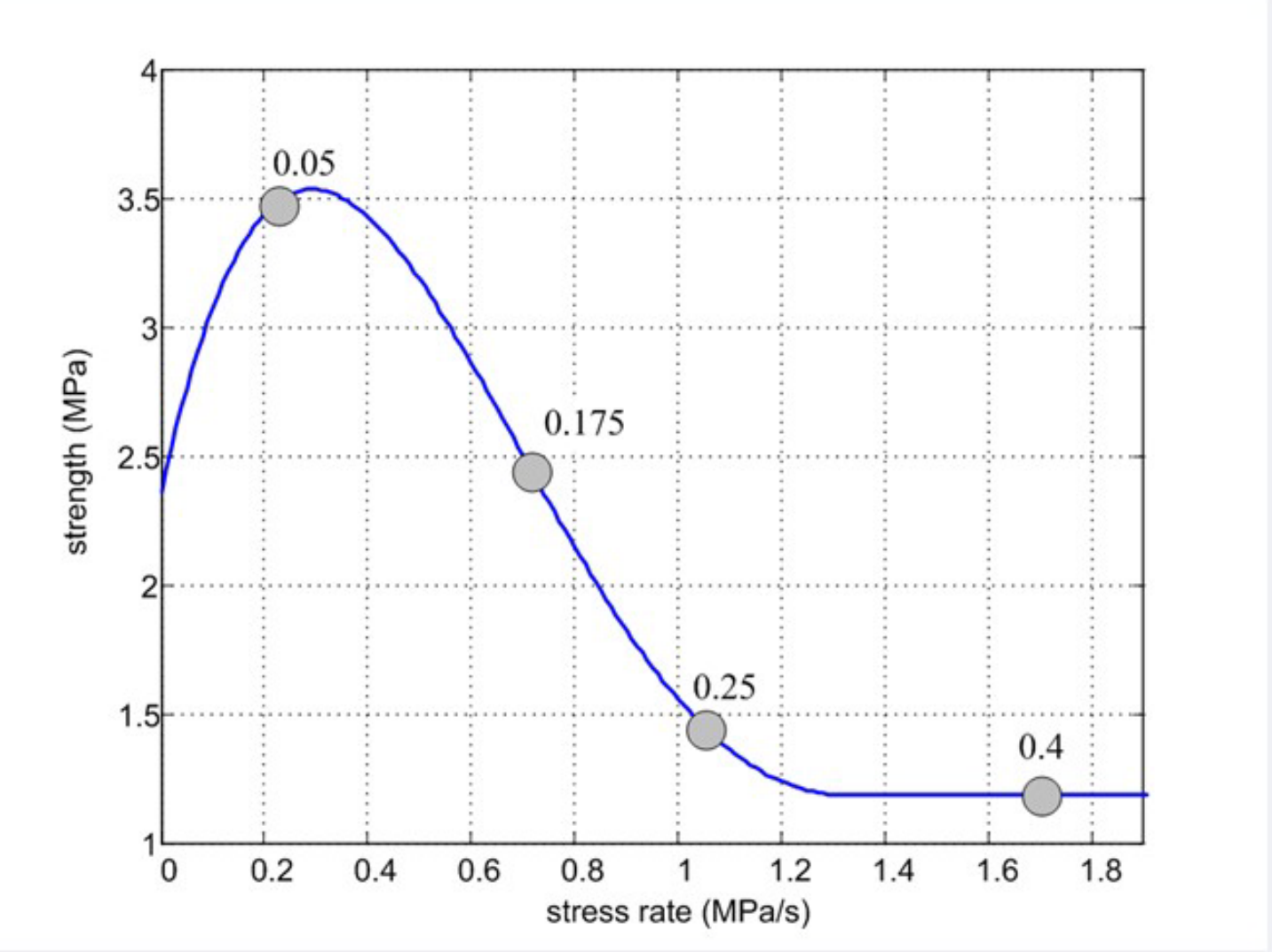

Figure 2. Ice crushing strength as a function of stress rate according to Määttänen-Blenkarn model. Average stress rates in the simulations for different ice velocities are shown by grey dots (the values indicate the ice velocity in m/s).

Results

Drifting sea ice induces dynamic load on the substructure. Both the amplitude and frequency content depends on the ice velocity. Because Määttänen-Blenkarn -model is based on uniaxial compression strength and its dependency on loading rate, the model has limited capability to describe various ice failure mechanisms in a complex ice-structure interaction process. However, the model is beneficial to find major challenges in ice load design:

- Ice load and ice induced structural vibrations depends strongly on the ice thickness and velocity. Therefore, site-specific ice conditions: ice thickness and drift are essential for the ice load design (*cf.* Tikanmäki *et al.* 2012)
- Displacement amplitude at the water level and tower top depends on the ice velocity (Fig. 4)
- In deeper water the support structures are more sensitive on ice-induced vibrations (Fig. 4)
- Significant ice-induced vibration occurs at the blade tip in fatigue point of view. Even though the amplitude due to ice is not vast, the oscillation frequency is higher than without ice.
- Moderate ice velocities 0.1 – 0.15 m/s induce most harmful vibrations (Figs. 3 and 4)
- Due to negligible aerodynamic damping in idling, larger vibration amplitudes at the tower top take place than in the operation mode (Fig. 4)
- The models of sub-structure were not exactly equivalent in the Abaqus and FAST causing some deviation in the displacement response especially n the higher water depth (20m)

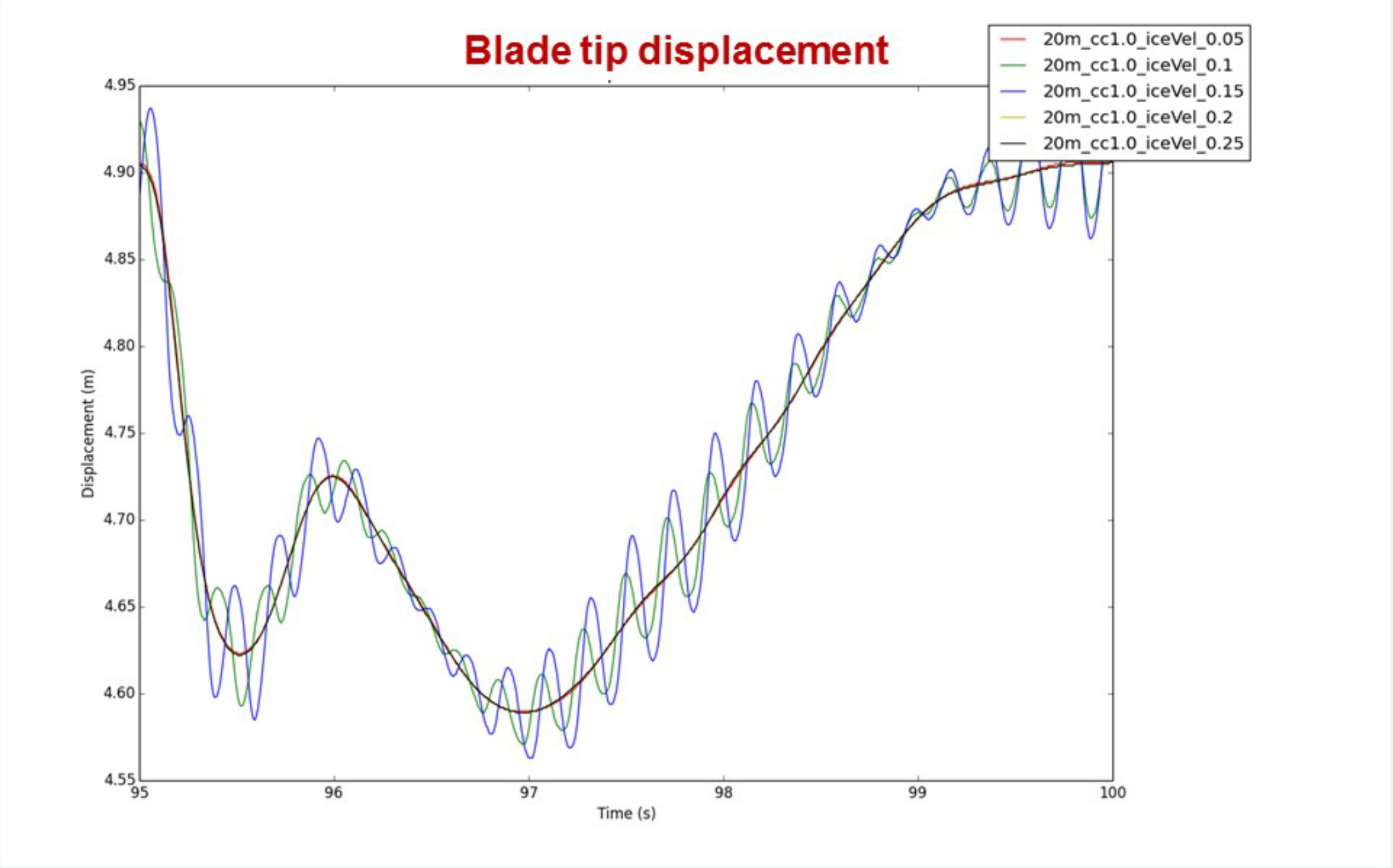

Figure 3. Time history slot of the blade tip displacement in fore-aft direction with different ice velocities, water depth 20m.

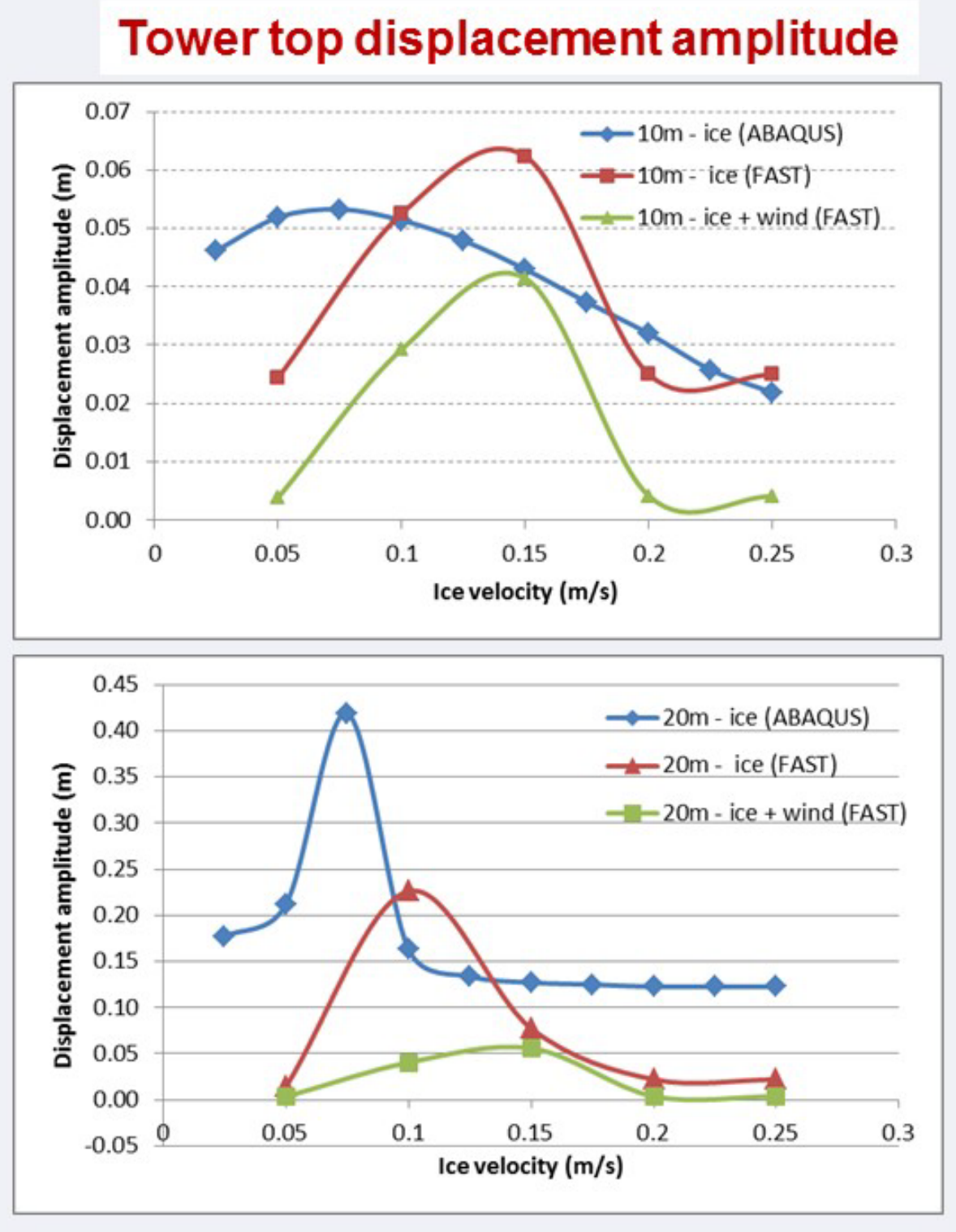

Figure 4. Displacement amplitudes at the tower top in fore-aft direction vs. ice velocity with different load combinations.

Conclusions

- Feasibility study of modelling structural dynamics in OWT in ice covered sea areas by using FAST introduced promising results. Various load combinations and operation modes can be considered by taking into account coupling between the ice, wind and structural response.
- Even though available IceFloe and IceDyn modules form a good basis to consider various ice load scenaria, FAST simulation tool together with an open programming interface creates a suitable development platform for further implementation of advanced ice load models (*cf.* Jussila et al.)
- As the ice load depends strongly on the structural deformations at the water level, coupled modelling is a necessary step to improve the accuracy of the ice load for the cost-efficient structural design
- Experimental verification in full-scale is needed for the model validation

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