A 2D test setup for scaled real-time hybrid tests of dynamic ice-structure interaction

Hammer, T.C.; van Beek, C.; Koning, J.R.A.; Hendrikse, H.

Publication date
2021

Document Version
Final published version

Published in
Proceedings of the 26th International Conference on Port and Ocean Engineering under Arctic Conditions

Citation (APA)
Hammer, T. C., van Beek, C., Koning, J. R. A., & Hendrikse, H. (2021). A 2D test setup for scaled real-time hybrid tests of dynamic ice-structure interaction. In *Proceedings of the 26th International Conference on Port and Ocean Engineering under Arctic Conditions: June 14-18, 2021, Moscow, Russia* (Proceedings of the International Conference on Port and Ocean Engineering under Arctic Conditions).. https://poac.com/Papers/2021/pdf/POAC21-024.pdf

A 2D test setup for scaled real-time hybrid tests of dynamic ice-structure interaction

Tim C. Hammer[1,3], Kees van Beek[2], Jeroen Koning[2], Hayo Hendrikse[1]
[1] Delft University of Technology, Department of Hydraulic Engineering, Delft, The Netherlands
[2] Delft University of Technology, DEMO, Delft, The Netherlands
[3] Siemens Gamesa Renewable Energy, The Hague, The Netherlands

ABSTRACT

With the ongoing development of offshore wind in cold regions where the foundations are exposed to sea ice, there is a strong need for data to validate the numerically predicted dynamic interaction between ice and structure used for design. Full-scale data is non-existent and only a limited number of experimental campaigns in ice tanks have been conducted for this specific problem. When compared to traditional structures subjected to sea ice loading like lighthouses and oil and gas platforms, the motion of the turbines at the ice action point is both in line with the ice drift direction but also significantly across due to the interaction of the turbine with the wind. Furthermore, the structure being slender overall and having a large top mass results in a very particular set of modes of oscillation where at least both the first and second global bending mode are expected to interact with the ice. To capture this complexity, a real-time hybrid test setup has been designed for basin tests in the SHIVER project and is presented in this paper. The setup uses two integrated linear actuators to control the motion of a rigid pile in two dimensions. Loads at the ice-action point are measured and used in a numerical model where these are combined with virtual loads, for example wind loading, to determine the response of the structure which is then applied in the physical setup by the actuators. The system allows to test a wide range of combinations of structural stiffness, mass, and damping, including structural properties typically associated with the relevant modes of oscillation of offshore wind turbines.

KEY WORDS: Ice-induced vibration; Model testing; Offshore wind turbine.

INTRODUCTION

Offshore wind turbines are installed more regularly in cold regions with the forecast of 83 GW installed capacity in the Baltic Sea compared to about 2.2 GW currently installed (Freeman *et al.*, 2019). Dynamic ice loading on support structures of the turbines can result in severe loads having to be dealt with. Offshore wind turbines are more compliant than any other existing structures that have been built in regions with seasonal sea ice, when accounting for the ice conditions for which they are typically designed. As a consequence, they are expected to experience more severe ice-induced vibrations as numerical simulations also indicate (Willems and Hendrikse, 2019). The typical design of an offshore wind turbine on monopile foundation results in the first two global bending modes to be easily excited by the ice. This results in a strong susceptibility for intermittent crushing and frequency lock-in (Figure 1). The latter is typically predicted to develop in the second global bending mode rather than the first global bending mode, something unique for this type of structure which has not been confirmed by any full-scale observations yet. The reason hereof is that there have simply not been any severe winters at those locations in Europe where most of the offshore wind turbines on monopile foundations which can be exposed to drifting sea ice are currently located.

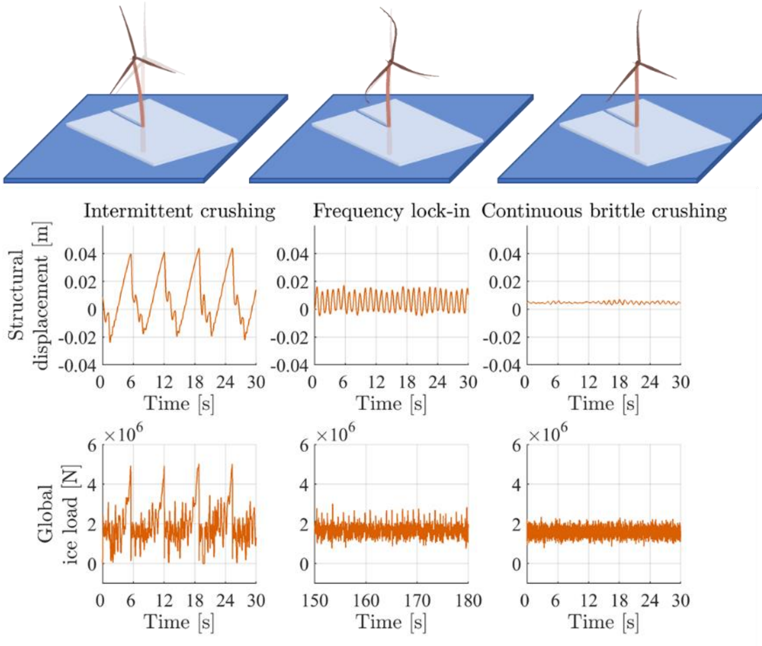

Figure 1 – Simulations of ice-structure interaction for an offshore wind turbine in ice indicate multimodal responses in which both support structure and rotor-nacelle-assembly participate. Results shown are for a typical offshore wind turbine on monopile foundation exposed to 50-year return period moving ice conditions in the southern Baltic Sea.

To gain further insight into the behaviour of offshore wind turbines in ice, a few model-scale test campaigns were conducted in the past. But to date, no suitable experimental data for ice-structure interaction of offshore wind turbines exist. Tian, Huang and Li (2019) made a scaled setup of an offshore wind turbine focussing on the first global bending mode only, capturing intermitting crushing and frequency lock-in; however, due to the oversimplification of the structural model, the results are not representative for an offshore wind turbine. Gravesen *et al.* (2005) do show occasions where frequency lock-in in the second global bending mode develops; however, the focus of their experiments was not on ice-induced vibrations. Additionally, intermittent crushing did not develop, potentially due to bending and buckling occurring often in the model ice used.

In the SHIVER research project, we aim to develop a model-scale benchmark dataset for offshore wind turbines exposed to drifting ice where the ice fails by crushing. For this purpose, it is important to develop a test setup that: 1) maintains the multi-degree-of-freedom characteristics and two-dimensional character of the structure and its motion, and 2) allows for introduction of wind loading, or the response of the structure due to wind loading. Here we present how we developed a setup which fulfils those two criteria after we first briefly discuss our view on scaling of dynamic ice-structure interaction which defined our choice for a hybrid test setup as opposed to a purely mechanical setup.

SCALING OF DYNAMIC ICE-STRUCTURE INTERACTION

It has proven challenging to define a meaningful physical equation for the problem of ice-induced vibrations which could serve as a basis for defining important dimensionless quantities which in turn can be used for scaling. Often scaling based on the Froude number and Cauchy number is still applied (Tian, Huang and Li, 2019), while gravity plays no role in ice-induced vibrations as long as the failure of the ice is in compression and buckling does not develop. The conclusion that ice can best be modelled by real ice by Palmer and Dempsey (2009) definitely applies to the problem we aim to investigate. As the latter is not (yet) possible, we have to somehow deal with the uncertainty related to the ice in the basin when designing our setup. For that reason, it is of interest to identify what dimensionless numbers may be governing this type of interaction and see how we can account for the uncertainty in the design of our test setup.

Most of the developed models for simulating ice-induced vibrations contain some empirical or phenomenological component which does not allow to fully express the equations in terms of physical quantities. Furthermore, certain theories assume the ice to behave in a purely elastic and brittle manner, whereas other theories include visco-elastic and visco-plastic deformation components in the ice associated with the development of damage, microcracking, recrystallization, etc., though often only in an approximate manner. Such differences lead to different sets of dimensionless numbers governing the problem of ice-induced vibrations.

Here we choose to derive the relevant dimensionless numbers from our current best understanding of the processes involved in the dynamic interaction (Hendrikse and Nord, 2019). This results in a list of relevant variables assuming the structure can be represented by multiple modes of oscillation i each with their natural frequency ω_i, damping ratio as a fraction of critical ζ_i, and modal mass m_i:

$$[\omega_1\ \zeta_1\ m_1\ \ddot{x}\ \dot{x}\ x\ w\ h\ v_{ice}\ E_1\ \sigma_c\ d\ \eta\ E_2\ ] \qquad [1]$$

, with x the displacement of the structure at the ice action point in the direction of ice loading, overdots representing derivatives with respect to time, w the projected width of the interaction zone, h the ice thickness, v_{ice} the ice drift speed, E_1 a modulus of elasticity defining the elastic deformation of ice under compressive loading, σ_c a representative crushing strength, d the average grain size of the ice, η a material coefficient of viscosity, and E_2 the elastic modulus defining the viscoelastic deformation. Note that we did not include the higher modes here as these can be simply made dimensionless in terms of their relative ratio to the first mode.

Table 1 – Dimensional matrix for the problem of ice-induced vibrations assuming the deformation of the ice to be governed by elastic and visco-elastic components and fracture to be brittle in local zones defined by a strength and the grain size as governing parameters. Note that we did not include the higher modes here as these can be simply made dimensionless in terms of their relative ratio to the first mode natural frequency, mass and damping ratio.

Dim	m_1	ζ_1	ω_1	$\ddot{x}$	$\dot{x}$	x	w	h	v_{ice}	E_1	σ_c	d	η	E_2
M	1	0	0	0	0	0	0	0	0	1	1	0	1	1
L	0	0	0	1	1	1	1	1	1	-1	-1	1	-1	-1
T	0	0	-1	-2	-1	0	0	0	-1	-2	-2	0	-1	-2

The dimensional matrix shown in Table 1 is obtained from the identified important variables. Application of the Buckingham Pi theorem, choosing σ_c, ω and d as repeating variables as these are of interest during the tests, results in the set of 11 dimensionless parameters defined in Eq. [2]. Note that we choose the grain size here rather than the more commonly chosen ice thickness as we consider local failure of the ice to be important and it may be represented better by grain size, or a characteristic length at that scale, than by ice thickness when it comes to crushing. Thickness and width do of course determine the global load to a large extent; however, these effects are relatively straightforward to define.

$$\boldsymbol{\pi} = \left[\frac{\sigma_c d}{m\omega^2}\ \zeta\ \frac{\ddot{x}}{d\omega^2}\ \frac{\dot{x}}{d\omega}\ \frac{x}{d}\ \frac{w}{d}\ \frac{v_{ice}}{d\omega}\ \frac{E_1}{\sigma_c}\ \frac{h}{d}\ \frac{\eta\omega}{\sigma_c}\ \frac{E_2}{\sigma_c}\right] \quad [2]$$

Here we recognize some relevant groups already proposed in literature such as the compliance ratio $\pi_1\pi_6 = \frac{\sigma_c dw}{m\omega^2 d} = \frac{\sigma_c hw}{kh}$ from the work by Kamesaki, Yamauchi and Kärnä (1996), the parameter proposed by Palmer, Qianjin and Fengwei (2010) to govern dynamic ice-structure interaction $\frac{\pi_7}{\pi_8} = \frac{v_{ice}}{h\omega}$, the 'Strouhal number for ice' introduced by Izumiyama and Uto (1997) given by $\pi_1\pi_5\pi_6\pi_8 = \frac{\sigma_c wh\omega}{kv_{ice}}$, the Elasticity control factor $\pi_1\pi_8\pi_9 = \frac{E_1 h}{k}$ and the rate control factor $\frac{\pi_6}{\pi_7} = \frac{w\omega}{v_{ice}}$ by Huang, Shi and Song (2007).

It is interesting to note that all of the earlier proposed dimensionless numbers can be obtained when assuming the problem to be a purely elastic-brittle problem in which the grain size, or a characteristic length for local failure, does not play a role, excluding d, η and E_2 as relevant parameters. In such a scenario, it would be appropriate to assure that for the model ice the ratio $\pi_8 = \frac{E_1}{\sigma_c}$ is maintained, and scaling of the other important variables follows by introducing some geometrical scale factor. The ratio $\frac{E_1}{\sigma_c}$ can be relatively well controlled as shown in the review by Lau, Wang and Lee (2007).

The grain size is the only geometrical parameter not typically controlled in experiments. It is not known to what extent the parent ice grain size and the damaged and recrystallized ice grain size which form during dynamic interaction in front of the indenter (Hirayama, Schwarz and Wu, 1974; Marchenko *et al.*, 2018) govern the interaction problem. In the latter case, the basin ice, which typically has smaller grains compared to parent ice in full-scale, would not be much different from the damaged and recrystallized ice in contact with the indenter in full-scale. This would allow us to apply a different scaling approach where natural frequency and velocity are not scaled and only a sufficiently high ratio $\frac{w}{d}$ and $\frac{h}{d}$ have to be maintained to avoid interaction with a single grain.

Adding the viscoelastic component to the equation, we introduce two additional dimensionless numbers of which one is a pure ice related number $\pi_{11} = \frac{E_2}{\sigma_c}$ and the other one links the ice and structural properties $\pi_{10} = \frac{\eta\omega}{\sigma_c}$. This last number is probably the most critical one as it relates the rate dependent ice behaviour to the dynamics of the structure. If the problem would be purely elastic and brittle, a change in natural frequency, assuming the damping ratio and stiffness of the structure to be constant, would only result in a change in $\pi_7 = \frac{v_{ice}}{d\omega}$. This suggests that for a higher natural frequency a higher ice drift speed would be required to obtain similar results between two tests or when comparing full-scale and model-scale results. The introduction of $\frac{\eta\omega}{\sigma_c}$; however, shows that when changing the natural frequency, we would have to additionally change either the viscosity or strength of the ice to get a similar result. The effect on basin tests for ice-induced vibrations would be significant, as the ratio $\frac{\eta}{\sigma_c}$ for model ice is typically not measured or controlled.

We conclude that complete scaling of the problem is not an option. This does not mean that we should disregard basin tests altogether. On the contrary, many basin tests show the interaction regimes observed for the full-scale structures and therefore the physics controlling the problem are present to some degree, regardless of how we adjust the ice to be used in the basin setting. This by itself is an interesting observation. We do believe that many general trends on the interaction can be understood from basin tests, provided that structures with different properties are tested in the same model ice conditions such that clear trends are actually captured.

TEST SETUP

The complexity associated with scaling as discussed above defines our test setup to a large extent. We want to have full control over the dynamic structural response in multiple vibration modes and two dimensions to generate relevant data for the behaviour of offshore wind turbines exposed to sea ice and wind loading. Furthermore, we want to be able to adjust the structural parameters easily to adapt to the ice conditions we will encounter in the basin. The latter is not easy with a purely mechanical setup. This is especially true when no scaling of time is applied, and a structure with a lowest natural frequency of 0.2 Hz has to be designed, but even more so when it comes to the ability to adjust the damping and relative importance of certain modes of vibration. In addition to these complexities, we would like to be able to add the response due to wind loading without having to make a scaled physical model of the full turbine.

A test setup fulfilling these requirements has been developed at TU Delft based on previous experience using linear actuators to control the motion of a structure in an ice basin (Hendrikse and Metrikine, 2016). The setup developed contains two motor integrated actuators that bidirectionally excite a rigid cylindrical structure by use of in-time measured strain in the cylinder close to the ice-structure interaction point. This real-time hybrid test method combines numerical and sub-structural stiffness in a dynamic analysis. When response delays between the numerical solution and physical excitation result in structural instability, actuator delay compensation methods can be implemented to add artificial damping into the system (McCrum and Williams, 2016).

An illustration of the components used in the real-time hybrid test setup is provided in Figure *2*. A structural model of an offshore wind turbine, or any other structure of interest, is defined (1) and uploaded into a purpose-built controller (2). The controller steers the motion of the physical setup that is connected to a carriage that drags the setup with a constant speed through the ice (3). As soon as the test setup is moving, the (close to) rigid pile in contact with the ice is excited and strain gauges at weakened positions inside the pile are used to indirectly measure the ice load (4) which is then forwarded to the controller. The controller solves the structural response numerically using a detailed structural model, adding virtual loading such as wind loading to the physically measured ice load and transfers the signal to reposition the rigid pile accordingly. The system runs at an update rate of 10 kHz.

Structural parts

The setup consists of three plates made of Aluminium (7075-T6-AlZnMgCu1,5). A honeycomb pattern was milled into the plates to reduce the overall mass. The top plate is connected to a support frame that later enables us to install the test setup in a predefined gap of the carriage. Four caged roller linear motion guides (SRG55C2SSC0 – 960LH LM Systems, 3905 TG Veenendaal, The Netherlands) are installed to allow linear motions of the plates, introducing minimal friction into the system. The overall setup has a mass of about 390 kg excluding the rigid pile which can be made in any shape or size depending on the structure of interest.

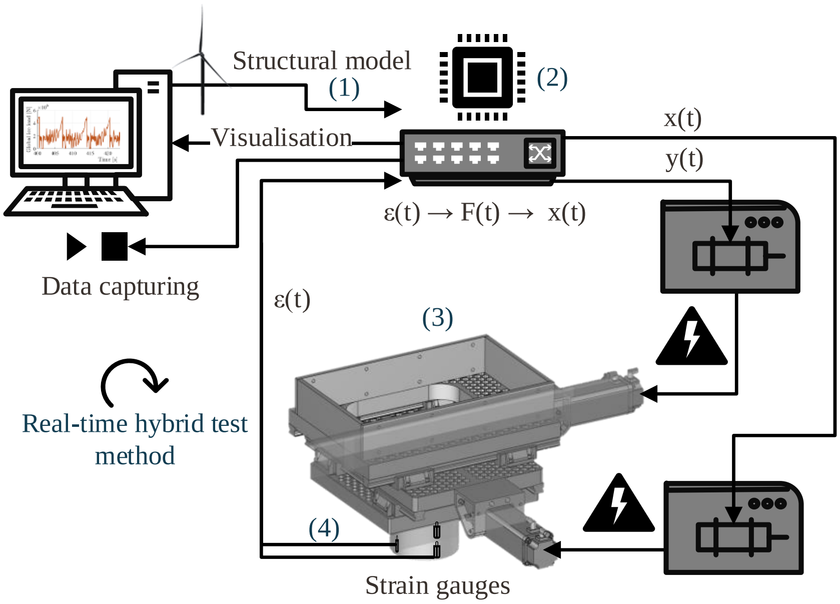

Figure 2 – (1) A structural model of a structure, in this case an offshore wind turbine including the model for the rotor-nacelle-assembly and wind loading, is uploaded in the software that is used by the controller (2). (3) The whole setup is pushed through the ice by a carriage crossing the ice basin. (4) Strain gauges inside the pile measure the strain due to ice loading which the controller (2) then converts to motion and sends as a signal to the actuators to move the rigid pile. Each of the actuators controls one direction of motion $x(t)$ and $y(t)$.

Measurement equipment

Several measurement devices are installed to capture the overall dynamic behaviour of the whole test setup (see Figure 3). The transfer system consists of two integrated motor actuators (GSX50-1005-MKR-SB5-358-G2 ACTUATION DIVISION - EXLAR Corporation, Eden Prairie MN 55346, USA) which move the plates while achieving a maximal stroke of 254 mm (6). They are each designed to withstand maximum loads of 19 kN and can provide a maximum speed of 508 mm/s. It is estimated that a maximum acceleration of 0.5 g can be reached while the actuator is loaded to its limit. Sixteen strain gauges (FLAB-6-11 ALTHEN BV Sensors & Controls, 2288 EL Rijswik, The Netherlands) in two rings at weakened positions on the inside of the pile measure the strain during ice loading (2). Two potentiometers (LCP8S-10-10K ETI Systems, Carlsbad CA 92008, USA) on the inside of the pile (3) are used to analyse the relative deflection of the pile in *x*- and *y*-direction. Magneto strictive displacement sensors (BIW0007-BIW1-A310-M0250-P1-S115 Balluff B.V., 5232 BC ‘s-Hertogenbosch, The Netherlands) are installed to analyse the displacement of the two tables (5). Load cells (VST5000 S-type load cell, HENK MAAS Weegschalen B.V., 4264 AW Veen, The Netherlands) are installed to verify our strain gauge measurements for further force identification (4). An accelerometer (ADXL326 Analog Devices Inc., Wilmington MS 01887, USA) on the inside of the pile can be used for determining inertial forces of the setup (1). Further accelerometers will be installed on each aluminum plate to allow to evaluate inertial forces while testing.

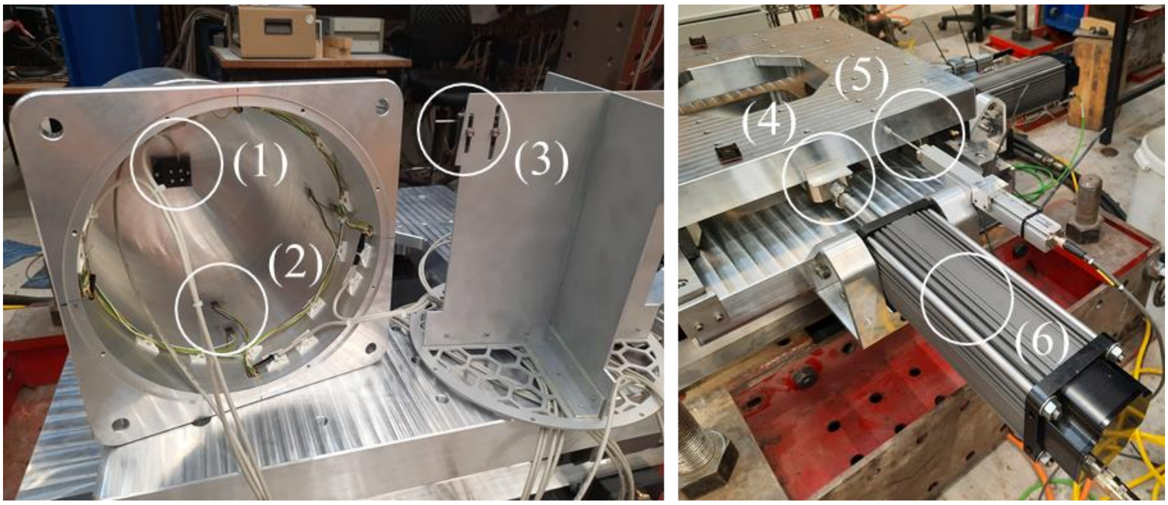

Figure 3 – (1) Accelerometer. (2) Strain gauges at weakened positions in pile. (3) Potentiometer to measure local deformation of the 'rigid pile'. (4) Load cell attached to the actuators. (5) Displacement sensors to measure the real displacement of the aluminium plates. (6) Integrated motor actuator.

NUMERICAL MODEL

The electrical actuators transfer the structural response provided by a numerical model in real-time. The model allows to solve a multi-degree-of-freedom oscillator with several sources of excitation (e.g. the measured ice load in combination with virtual wind and current loading) and is solved in the modal domain resulting in the following equation of motion:

$$\ddot{w}_i(t) + 2 \cdot \zeta_i \cdot \omega_i \cdot \dot{w}_i(t) + \omega_i^2 \cdot w_i(t) = \frac{\phi_{i,ice}}{m_i^*} F_{ice}(t) + \frac{\boldsymbol{\phi}^T}{m_i^*} \boldsymbol{F}_{virtual}(t) \quad [3]$$

with $w_i(t)$ the modal displacement of mode i at time t, where the overdots represent derivatives with respect to time. The modal mass entry is represented by m_i^*, here equal to 1 as we mass-normalise the eigenmodes with $\boldsymbol{\phi}^T \cdot \boldsymbol{M} \cdot \boldsymbol{\phi} = \boldsymbol{I}$, and $\phi_{i,ice}$ is the modal amplitude at the ice-action point. ω_i represents the natural frequency of mode i, ζ_i the damping as a fraction of critical, and $F_{ice}(t)$ the measured load at the ice-action point. The term $\frac{\boldsymbol{\phi}^T}{m_i^*} \boldsymbol{F}_{virtual}(t)$ concerns all the virtually added loads such as wind loading which can be applied at any point along the structure.

The equation of motion is solved in real-time using the Euler-Cromer algorithm for each iteration step j:

$$\dot{w}_i(t_{j+1}) = \dot{w}_i(t_j) + \Delta t \cdot \left(\frac{\phi_{i,ice}}{m_i^*} F_{ice}(t_j) + \frac{\boldsymbol{\phi}^T}{m_i^*} \boldsymbol{F}_{virtual}(t_j) - 2 \cdot \zeta_i \cdot \omega_i \cdot \dot{w}_i(t_j) - \omega_i^2 \cdot w_i(t_j) \right) \quad [4]$$

and

$$w_i(t_{j+1}) = w_i(t_j) + \dot{w}_i(t_{j+1}) \cdot \Delta t \qquad [5]$$

The displacements to be imposed on the rigid cylinder in the physical setup are determined from the product of the modal displacements and the eigenvectors as:

$$y(t) = \sum_i^n \phi_{i,ice} \cdot w_i(t) \qquad [6]$$

The software is implemented for each axis, allowing to create structural responses of $y(t)$ and $x(t)$ simultaneously. Different algorithms can be implemented straightforwardly to deal with added wind loading and/or predefined oscillation patterns of the structure for forced vibration experiments.

RESULTS OF PRE-TESTING THE DRY SETUP

In the Stevin-2 laboratory of TU Delft, we installed the above presented setup and tested if the system can simulate responses expected to result during ice model tests. As we could not actively excite the pile with an ice sheet, we used predefined ice loads, simulated with the ice-structure interaction model from Hendrikse and Nord (2019), as load input for our transfer system. We present results of structural responses for an intermittent crushing (ICR), frequency lock-in (FLI) and continuous brittle crushing (CBC) event that have been adjusted for a recognized time delay (see Figures 4-6). The structural model used for these pre-tests has been developed at Siemens Gamesa Renewable Energy and consists of the modes of an offshore wind turbine up to 20 Hz adjusted to account for the reduced load on the structure in the ice basin expected in the range of 2.5 kN for the mean load in continuous brittle crushing.

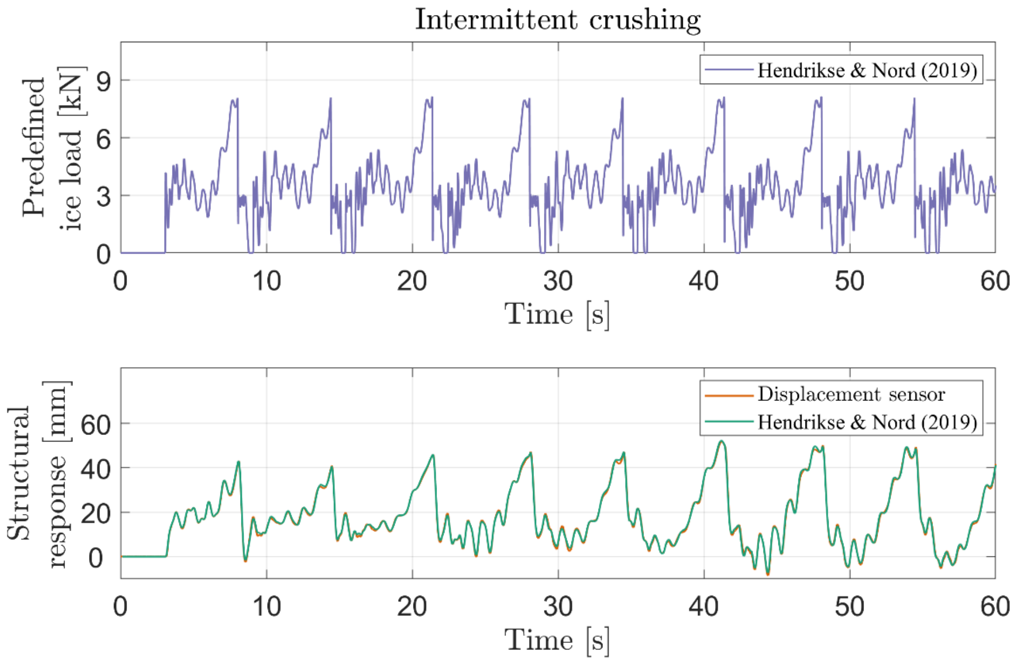

Figure 4 – A predefined ice load, representative for ICR, is used as input for our numerical model and the ice-structure interaction model by Hendrikse and Nord (2019). The

comparison shows that the setup is capable of controlling the motion expected to occur for an ICR event.

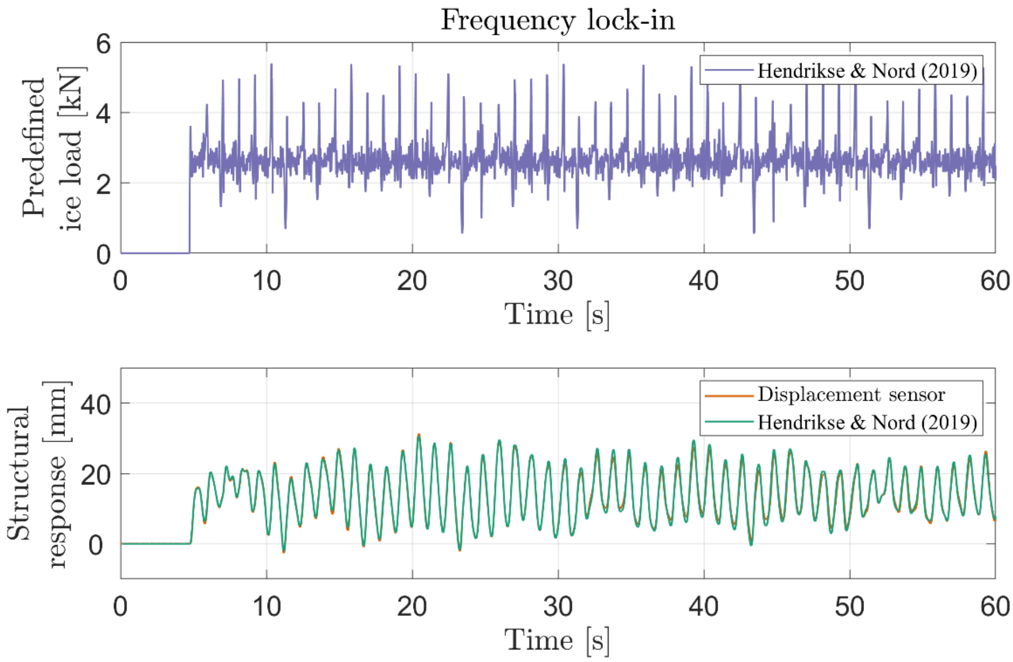

Figure 5 – A predefined ice load, representative for FLI, is used as input for our numerical model and the ice-structure interaction model by Hendrikse and Nord (2019). The comparison shows that the setup is capable of controlling the motion expected to occur for a FLI event.

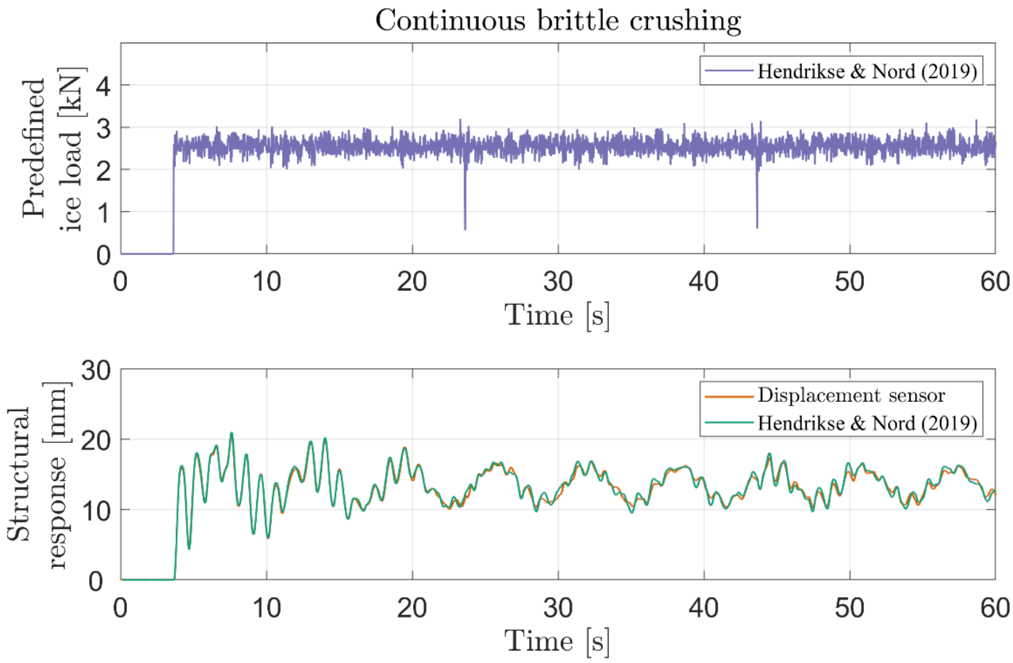

Figure 6 – A predefined ice load, representative for CBC, is used as input for our numerical model and the ice-structure interaction model by Hendrikse and Nord (2019). The comparison shows that the setup is capable of controlling the motion expected to occur for an

CBC event.

To simulate a structural response under physical loading, the pile was pushed into a wooden beam (see Figure 7). Under a medium load of on average 4.0 kN, we were able to test the system under a virtually applied continuous brittle crushing response signal (see Figure 8). The setup showed to be capable of controlling the motion of the structure while under varying resistance provided by the wooden beam.

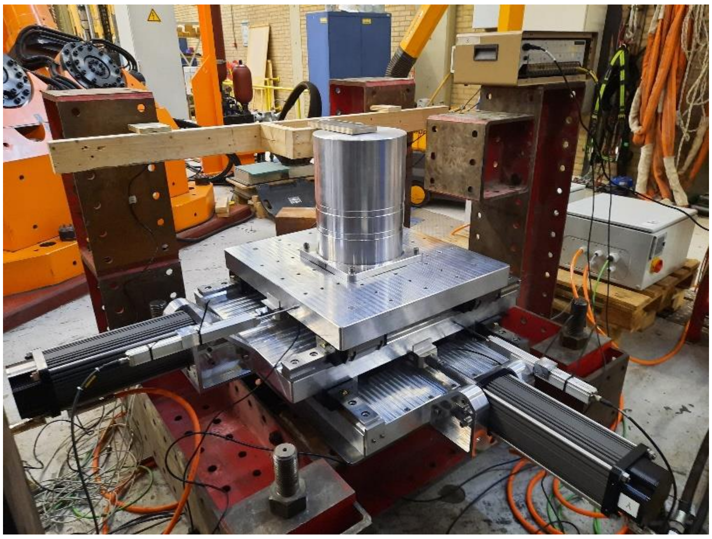

Figure 7 – The pile is pushed with a predefined structural response against a wooden beam to test if the setup is capable to control the predefined structural response under loaded conditions.

The pre-test campaign showed that the setup is capable to transfer predefined motions sufficiently and that the guide rails contribute low frictional forces (< 30 N). The experiment in Figure 7 gives us confidence that the actuators will be able to control the motion for the load levels we anticipate in the basin, though it is noted that representative external loading is missing from these 'dry' tests.

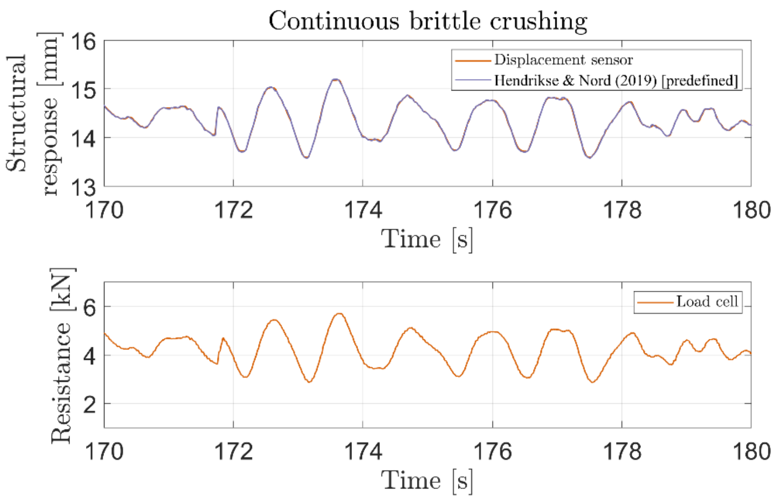

Figure 8 – Measurement of the response of the system under pre-defined displacement representative of continuous brittle crushing and a physical resistance by the wooden beam of on average 4.0 kN.

FIRST RESULTS FROM PRELIMINARY ICE TANK TESTS

First results from the ongoing test campaign in the ice tank of Aalto university show that the developed 2D test setup is capable to simulate the multi-modal structural response in 2D during dynamic ice-structure interaction. As an example, we present the structural response in the ice drift direction, measured ice load and relative velocity between ice and structure for a simulated offshore wind turbine interaction with ice (Figure 9). It is noted that for this trial run the ice was merely a thin frozen layer of about 6 mm thick ice to test the system under loaded conditions and therefore the crushing failure was interrupted often by global bending failure, most likely induced by buckling of the ice sheet. Nevertheless, we observed strong interaction with the first and second global bending mode of the wind turbine at low speed (Left and Middle plot) and a response typical for continuous brittle crushing at high indentation speed (Right).

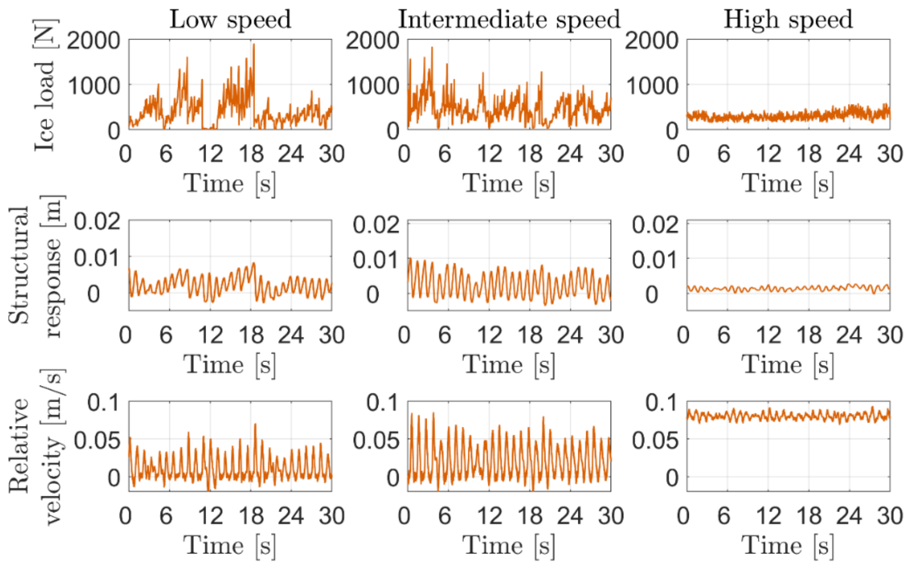

Figure 9 – First results from tests at the Aalto ice tank on the 28th of May 2021, show that different ice-structure interaction regimes can be simulated with the setup. Left: low speed test at 10 mm/s showing interaction with the first and second global bending mode of the structure; Middle: intermediate test showing tendencies of frequency lock-in in the second global bending mode at 20 mm/s; Right: high speed continuous brittle crushing at 80 mm/s.

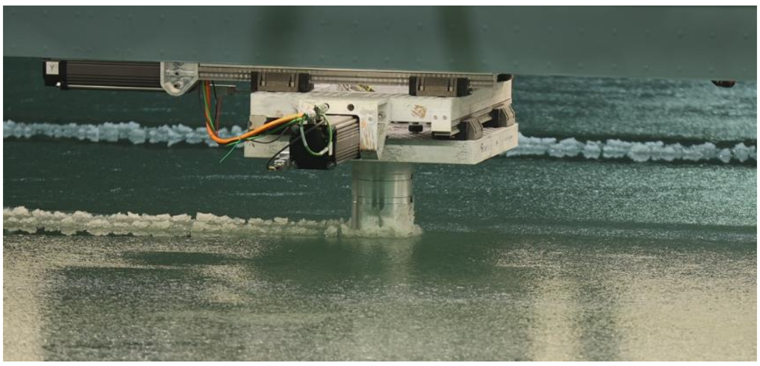

Figure 10 – A picture of the test setup in a frozen layer of water with ethanol during the first trial run conducted in the ice tank of the Aalto university in Finland on the 28th of May, 2021.

CONCLUSION

To create a model-scale benchmark dataset for offshore wind turbines exposed to drifting ice where the ice fails in crushing, it is important to develop a test setup that: 1) maintains the multi-degree-of-freedom characteristics and two-dimensional character of the structure and its motion, and 2) allows for introduction of wind loading, or the response of the structure due to wind loading. Scaling of dynamic ice-structure interaction is uncertain when using weakened model ice rather than real saline or freshwater ice which makes it difficult to define the dynamic structural properties to be used in a model test. It is therefore necessary to have flexibility in the test setup allowing to adjust the structural properties based on the ice conditions in the basin.

We developed a test setup which can be used for simulating the response of an offshore wind turbine, or any type of structure in ice, fulfilling the requirements as formulated above. The setup uses a real-time hybrid test method where two actuators transfer the motion to a rigid physical model which can have different shapes and of which the size can easily be adjusted. A controller is used to define the motion to be applied based on a numerical model for the structure. This allows for testing of any type of structure from single-degree-of-freedom oscillators to multi-modal representations in two dimensions with added virtual loading by wind and currents with full control over the structural mass, damping and stiffness.

Testing with the setup at the Aalto ice tank was delayed due to COVID-19 travel restrictions and is ongoing during the conference where this work is presented. First results included here show that the system is stable under conditions where the ice load is small (< 2 kN) and can be used to simulate multi-modal interaction with ice.

ACKNOWLEDGEMENTS

The authors thank the participating organizations in the SHIVER project: TU Delft, Siemens Gamesa Renewable Energy, and Aalto University, for supporting this work. The SHIVER project is co-financed by Siemens Gamesa Renewable Energy and TKI-Energy by the ‘Toeslag voor Topconsortia voor Kennis en Innovatie (TKI’s)’ of the Dutch Ministry of Economic Affairs and Climate Policy.

We further thank Knut Høyland for his contribution in discussions on scaling and Tom Willems and Cody Owen for their contributions in discussions on development of the test setup. We thank the crew of the Aalto ice tank: Otto Puolakka, Teemu Päivärinta, Lasse Turja and Sampo Hanhirova, for their help in preparation and installation of the setup and execution of the first tests.

REFERENCES

Freeman, K. *et al.* (2019) ‘Our Energy Our Future - How offshore wind will help Europe go carbon-neutral’, *WindEurope*.

Gravesen, H. *et al.* (2005) ‘Ice loading on Danish wind turbines: Part 2. Analyses of dynamic model test results’, *Cold Regions Science and Technology*, 41(1), pp. 25–47. doi: 10.1016/j.coldregions.2004.05.009.

Hendrikse, H. and Metrikine, A. (2016) ‘Edge indentation of ice with a displacement-controlled oscillating cylindrical structure’, *Cold Regions Science and Technology*. Elsevier B.V., 121, pp. 100–107. doi: 10.1016/j.coldregions.2015.10.013.

Hendrikse, H. and Nord, T. S. (2019) ‘Dynamic response of an offshore structure interacting with an ice floe failing in crushing', *Marine Structures*, 65, pp. 271–290. doi: 10.1016/j.marstruc.2019.01.012.

Hirayama, K., Schwarz, J. and Wu, H.-C. (1974) *An investigation of ice forces on vertical structures*. Iowa City, Iowa, USA.

Huang, Y., Shi, Q. and Song, A. (2007) 'Model test study of the interaction between ice and a compliant vertical narrow structure', *Cold Regions Science and Technology*, 49(2), pp. 151–160. doi: 10.1016/j.coldregions.2007.01.004.

Izumiyama, K. and Uto, S. (1997) 'Ice loading on a compliant indentor', in Yamaguchi, H. et al. (eds) *Proceedings of the 16th International Conference on Offshore Mechanics and Arctic Engineering*. Yokohama, Japan: OMAE, pp. 431–436.

Kamesaki, K., Yamauchi, Y. and Kärnä, T. (1996) 'Ice force as a function of structural compliance', in *Proceedings of the 13th IAHR International Symposium on Ice*. Beijing, China: IAHR, pp. 395–402.

Lau, M., Wang, J. and Lee, C. (2007) 'Review of ice modeling methodology', *Proceedings of the International Conference on Port and Ocean Engineering under Arctic Conditions, POAC*, pp. 350–362.

Marchenko, A. V. *et al.* (2018) 'Scale effects in compressive strength of sea ice', *24th IAHR International Symposium on Ice. Vladivostok, Russia, June4 to June 8, 2018*, pp. 37–52.

McCrum, D. P. and Williams, M. S. (2016) 'An overview of seismic hybrid testing of engineering structures', *Engineering Structures*. Elsevier Ltd, 118, pp. 240–261. doi: 10.1016/j.engstruct.2016.03.039.

Palmer, A. and Dempsey, J. (2009) 'Model tests in ice', in *Proceedings of the 20th International Conference on Port and Ocean Engineering under Arctic Conditions*. Luleå, Sweden: POAC.

Palmer, A., Qianjin, Y. and Fengwei, G. (2010) 'Ice-induced vibrations and scaling', *Cold Regions Science and Technology*. Elsevier B.V., 60(3), pp. 189–192. doi: 10.1016/j.coldregions.2009.11.005.

Tian, Y., Huang, Y. and Li, W. (2019) 'Experimental Investigations on Ice Induced Vibrations of a Monopile-type Offshore Wind Turbine in Bohai Sea', in *Proceedings of the 29th International Ocean and Polar Engineering Conference,* pp. 327–334.

Willems, T. and Hendrikse, H. (2019) 'Coupled simulation of ice-structure interaction of offshore wind turbines in BHawC using VANILLA', in *Proceedings of the 25th International Conference on Port and Ocean Engineering under Arctic Conditions*.