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CLASSIFICATION OF ICE-INDUCED VIBRATION REGIMES OF OFFSHORE WIND TURBINES

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ABSTRACT
Ice-induced vibrations of offshore wind turbines on monopile foundations were investigated experimentally at the Aalto Ice Tank. A real-time hybrid test setup was developed allowing to accurately simulate the motion of a wind turbine in interaction with ice, incorporating the multi-modal aspects of the interaction and the effect of simultaneous ice and wind loading. Different vibration patterns were observed where some could be described based on the common terminology of intermittent crushing or continuous brittle crushing. However, not all resulting vibrations could be described accordingly. A combination of several global bending modes interacting with the ice resulted in high global ice loads and structural response. Such response is likely typical for an offshore wind turbine, owing to the dynamic characteristics of the structure. The type of interaction observed during the tests would be most critical for design as the largest bending moments in critical cross-sections of the foundations occur for this regime. A classification of ice-induced vibrations is proposed which encompasses the experimental observations for offshore wind turbines on the basis of the periodicity in the structural response at the ice action point.

Keywords: ice tank tests, ice-structure interaction, multi-modal interaction, dynamic ice loading

1. INTRODUCTION
Offshore wind farms are planned in regions with rougher environmental conditions to respond to the rising demand of renewable energy. As one path of offshore wind expansion, offshore wind projects are planned in sub-arctic regions more frequently. For such regions, it is required to consider sea ice during the design phase of an offshore wind turbine. Sea ice and its dynamic effects on vertical structures have been investigated in the past for oil- and gas structures [1]. However, as the dynamic properties of those structures significantly differ from those of an offshore wind turbine, there is a need for new research on ice-structure interaction.

The main guideline for the design of offshore structures for dynamic ice loads, the ISO19906 [2], defines three ice-structure interaction regimes: intermittent crushing, frequency lock-in and continuous brittle crushing. Continuous brittle crushing is defined as a ‘random ice action and response of the structure’. Frequency lock-in is defined as ‘an amplified structural response significantly caused by a resonant behavior, which, for Baltic Sea structures, develops for ice drift speeds between 0.04 and 0.10 m/s’. Intermittent crushing is described to result in both ice action and structural displacement in ‘a sawtooth pattern’ as the consequence of loading phases with low relative velocities and unloading phases of high relative velocity.

The design standard for offshore wind turbine support structures IEC61400-3-1 [3] refers to ISO19906 in relation to ice loading and dynamic ice-structure interaction. Intermittent crushing and continuous brittle crushing are not mentioned there, but the focus is rather on ‘frequency lock-in’. Reason for that might be that ‘frequency lock-in’ is still referred to as resonance and therefore considered most severe for the structure, which will be discussed later.

Recent research on the topic of ice loads on offshore wind support structures also focused mainly on ‘frequency lock-in’ and typically looked at mitigation methods [4-6]. These analyses skip an important question that should first be answered: What type of dynamic ice-structure interaction develops for offshore wind turbines, and how does it impact the design? Instead, it is assumed that the models derived for lighthouses and oil- and gas structures are relevant for wind turbines as well [7].

Experiments were performed at the Aalto Ice Basin as part of the SHIVER project in an attempt to answer the question of how the interaction between offshore wind turbines and ice develops [8]. Analysis of the data showed the development of multi-modal ice-structure interaction for offshore wind turbines [9]. This paper summarizes the experimental observations with focus on requirements that these may impose on the design of offshore wind turbines. This allows to discuss the terminology of ice-induced vibrations and to propose a classification scheme based on the periodicity of the structural response signals.

2. MATERIALS AND METHODS

To obtain model-scale data of an offshore wind turbine in ice, a real-time hybrid test setup was developed at TU Delft [10] and used during ice tank tests at Aalto University, Finland. Detailed information about the test campaign can be found in [8]. The data from the campaign are publicly available from [11].

A hybrid test setup combines a physical test setup, including a measurement system, with a numerical model. Identified ice forces are used to calculate the structural response numerically and apply these displacements in real-time. Therefore, one electrical linear-motor actuator had been installed in the direction of towing carriage motion (ice drift) and one perpendicular to it. The setup allowed to apply structural responses in two directions, including displacements caused by external forces, like wind, even in a misaligned load condition. The drifting ice was simulated by dragging the whole setup through the ice by a moveable carriage that was mounted to a bridge spanning the ice basin (Figure 1).

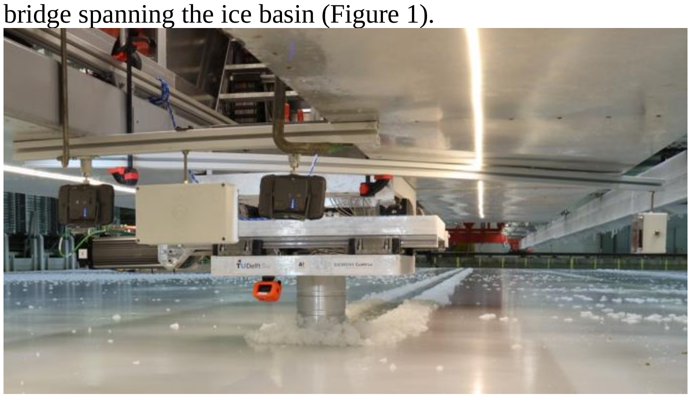

FIGURE 1: A REAL-TIME HYBRID TEST SETUP HAS BEEN USED IN ICE TANK TESTS AT AALTO UNIVERSITY IN FINLAND TO CONDUCT MODEL-SCALE EXPERIMENTS OF OFFSHORE WIND TURBINES IN ICE.

The pile has been manufactured as stiff as possible to guarantee that local displacements are minimized (d<10µm). Prepared sections of smaller wall thickness were used for strain measurements. The data was captured with a sampling frequency of 2 kHz.

The structural model implemented in the numerical part of the setup was scaled against an estimated mean brittle ice load in the ice tank to result in unscaled structural responses. We thereby fulfilled scaling requirements suggested by [12]. These requirements impose that neither time nor length should be scaled for ice-structure interaction tests.

In an attempt to validate the applicability of our scaling approach, we tested simplified structural models of offshore structures that experienced ice-induced vibration and compared the test results to full-scale observations. Results are shown at this conference [13].

Particular tests used in this paper are referred to by their respective test ID which can be found in the database included in [11].

3. EXPERIMENTAL RESULTS AND CLASSIFICATION

This chapter summarizes the main experimental observations of ice-structure interaction for offshore wind turbines and concludes with the introduction of a classification scheme based on the structural response at the ice action point. All data presented are raw data, when not indicated differently. Ice loads presented are scaled to full-scale with the applied scaling factor. Amplitude spectral densities shown are based on the presented time span.

3.1 Continuous brittle crushing

The ice load for high ice drift speeds (here roughly 0.075 m s^{-1}, Figure 2) is characterized as a stochastic process around a roughly constant mean value. The load signal has no obvious periodicity, neither has the structural displacement, as indicated by time series and the amplitude spectral density (ASD). The load results in a small-amplitude oscillation of the structure around a mean displacement and high relative velocity between structure and the ice.

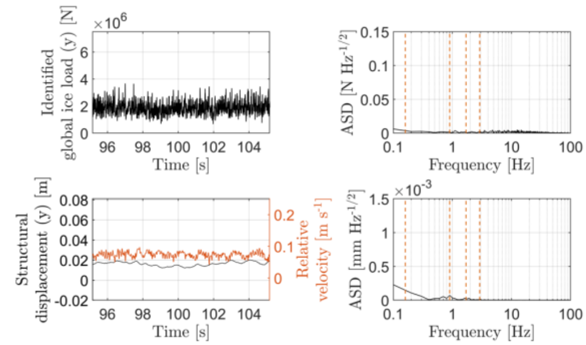

FIGURE 2: IDLING TURBINE AT 0.075 M S^{-1} (TEST 589). TOP LEFT: ICE LOADS TYPICAL FOR CONTINUOUS BRITTLE CRUSHING CAN BE DEFINED AS A STOCHASTIC PROCESS AROUND A CONSTANT MEAN VALUE. TOP RIGHT: THE AMPLITUDE SPECTRAL DENSITY OF THE ICE LOAD, ORANGE DASHED LINES INDICATE NATURAL FREQUENCIES OF THE STRUCTURE. BOTTOM LEFT: THE STRUCTURAL DISPLACEMENT AND RELATIVE VELOCITY BETWEEN ICE AND STRUCTURE. BOTTOM RIGHT: THE AMPLITUDE SPECTRAL DENSITY OF THE STRUCTURAL DISPLACEMENT.

3.2 Multi-modal interaction-II

The ice load for an intermediate ice drift speed (here 0.04 m s^{-1}) has been observed to result in higher maximum but similar mean ice loads as for continuous brittle crushing (Figure 3). The structural response shows a clear periodicity which is also apparent in the ice load time series. At the moment of larger ice failure, the unloading phase, the structural displacement has a slightly steeper slope than during the loading phase. The latter can be characterized as the phase during which the relative velocity between the ice and structure remains around zero.

The amplitude spectral density of the structural response indicates that the structure vibrates with the second and third mode contributing, though at a slightly lower frequency as a result of interaction with the ice. The third mode vibration only occurs during phases with minimum relative velocity, appearing as a small oscillation in the structural displacement during a loading phase.

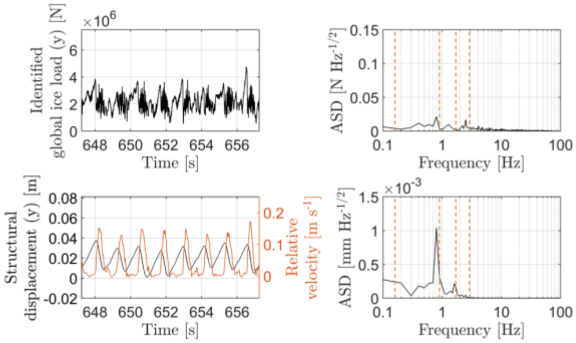

FIGURE 3: IDLING TURBINE AT 0.04 M S^{-1} (TEST 601). TOP LEFT: ICE LOADS TYPICAL FOR MULTI-MODAL INTERACTION, DOMINATED BY THE SECOND MODE, ARE DEFINED BY A MIXTURE OF BRITTLE CRUSHING AND LOAD BUILD UPS. TOP RIGHT: THE AMPLITUDE SPECTRAL DENSITY OF THE ICE LOAD. BOTTOM LEFT: THE STRUCTURAL DISPLACEMENT REVEALS A LOADING AND UNLOADING PHASE. RELATIVELY LONG PHASES OF A RELATIVE VELOCITY AROUND ZERO OCCUR. BOTTOM RIGHT: THE AMPLITUDE SPECTRAL DENSITY OF THE STRUCTURAL DISPLACEMENT.

3.3 Multi-modal interaction-I

High peaks are observed in the ice load for low ice drift speeds (here 0.020 m s^{-1}) (Figure 4). Peak loads develop after a long phase of low relative velocity between the ice and structure. In between the moment of a large load drop and start of a new build up phase, the ice load resembles that of multi-modal interaction-II introduced in Section 3.2.

The structural response indicates periodic saw-tooth patterns like for intermittent crushing, whereas the loading and unloading phase almost have the same steepness. During the unloading phase the structure experiences vibrations in the second and sometimes third mode, comparable to those observed in Figure 3. The reason seems to be that due to the low first natural frequency of the structure the relative velocity between the structure and the ice during the structure's reversal motion stays in the range where second and third mode vibrations can be excited. We expect that this would not be observed for structures with a much faster responding first mode as the relative velocity between ice and structure changes more quickly in such case.

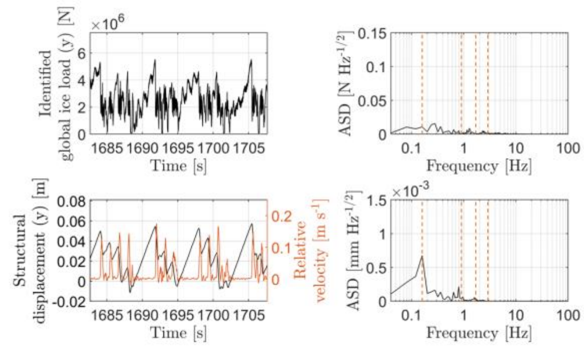

FIGURE 4: IDLING TURBINE AT 0.02 M S^{-1} (TEST 593). TOP LEFT: ICE LOADS SHOW A MIXTURE OF HIGHER LOAD BUILD UPS AND LOAD PATTERNS TYPICAL FOR MULTI-MODAL INTERACTION-II. TOP RIGHT: THE AMPLITUDE SPECTRAL DENSITY OF THE ICE LOAD. BOTTOM LEFT: THE STRUCTURAL DISPLACEMENT SHOWS THAT THE LOADING AND UNLOADING PHASE HAVE SIMILAR STEEPNESS. DURING THE UNLOADING PHASE RELATIVE VELOCITIES CAUSE SECOND AND THIRD MODE VIBRATIONS. BOTTOM RIGHT: THE AMPLITUDE SPECTRAL DENSITY OF THE STRUCTURAL DISPLACEMENT.

3.4 Intermittent crushing

For the lowest tested ice drift speed (here 0.005 m s^{-1}), maximum global ice loads have been observed in the test (Figure 5). This quasi-static regime shows long phases of load build-up with severe, rapid load drops upon global ice failure. The ASD of the global ice load indicates that mainly frequencies below the first eigenmode are present in the signal.

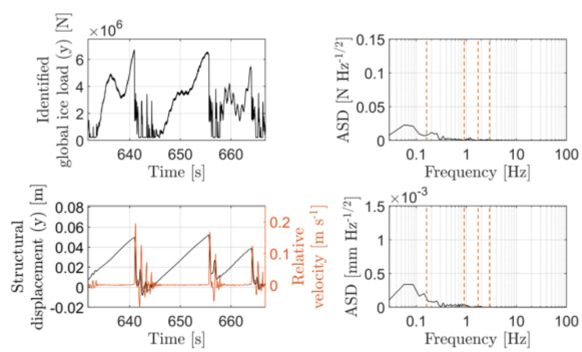

FIGURE 5: IDLING TURBINE AT 0.005 M S^{-1} (TEST 590). TOP LEFT: ICE LOADS SHOW THE HIGHEST PEAKS DURING INTERMITTENT CRUSHING. TOP RIGHT: THE AMPLITUDE SPECTRAL DENSITY OF THE ICE LOAD INDICATES THAT FREQUENCIES LOWER THAN THE FIRST EIGENMODE ARE DOMINANT. BOTTOM LEFT: THE STRUCTURAL DISPLACEMENT SHOWS TYPICAL SAW-TOOTH PATTERNS WITH A FREQUENCY BELOW THE FIRST EIGENFREQUENCY. BOTTOM RIGHT: THE AMPLITUDE SPECTRAL DENSITY OF THE STRUCTURAL DISPLACEMENT.

After a load drop, the structure crushes with high relative velocity through the ice. The high relative velocities result in short phases of continuous brittle crushing. Once the structure moves in the same direction as the ice, but faster, contact might be lost. During the decay of the structural vibration several events of contact loss can occur, resulting in load drops to zero or more specific to the value of remaining external load (here: hydrostatic load).

3.5 ‘Frequency lock-in’

Additionally, we show results of ‘frequency lock-in’. This regime can only occur for structures for which the interaction with ice is governed by a single mode, such as for single-degree-of-freedom (SDOF) oscillators. Results of an SDOF structure tested during the test campaign are shown in (Figure 6). The structural frequency is equal to the second eigenmode of the tested offshore wind turbine.

The ice load signal does not seem to differ significantly from the load signal for multi-modal interaction-II (see Figure 3). The structural displacement shows a quasi-harmonic structural response. In contrast to Figure 3, relative velocities indicate a near-harmonic pattern too for the SDOF oscillator. It is important to appreciate that an offshore wind turbine is not likely to experience such classical ‘Frequency lock-in’ due to its dynamic properties which allow the ice to easily excite multiple modes.

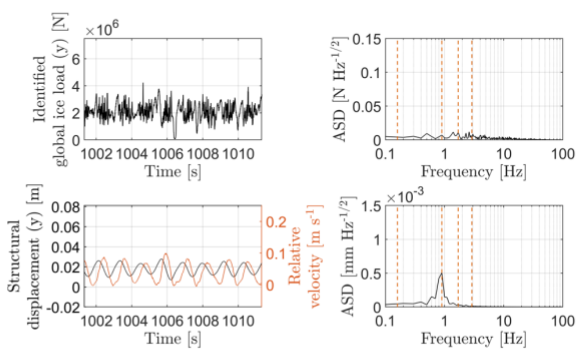

FIGURE 6: SDOF STRUCTURE AT ~ 0.037 M S^{-1} (TEST 410). TOP LEFT: ICE LOADS SHOW SIMILAR LOAD SIGNAL AS FOR MULTI-MODAL INTERACTION-II. TOP RIGHT: THE AMPLITUDE SPECTRAL DENSITY OF THE ICE LOAD. BOTTOM LEFT: THE STRUCTURAL DISPLACEMENT SHOWS A QUASI-HARMONIC RESPONSE AROUND THE FIRST (AND ONLY) EIGENFREQUENCY. BOTTOM RIGHT: THE AMPLITUDE SPECTRAL DENSITY OF THE STRUCTURAL DISPLACEMENT.

3.6 Classification scheme

In summary we suggest that ice-induced vibration types can be classified by their periodicity (Figure 7). If neither the time series of structural displacement nor the time series of a global ice load indicate periodicity, the structure is not interacting significantly with the ice and vice versa. Hence, we classify this as an action problem rather than an interaction problem which is referred to as ‘continuous brittle crushing’ in keeping with existing design standards.

Once any periodicity is observable, interaction is likely to have taken place between ice and structure. If the global frequency of interaction is well below the first eigenfrequency of the structure, the vibration can be classified as intermittent crushing as commonly done (ICR).

If any interaction at frequencies close to a natural frequency occurs, vibrations can either be classified as multi-modal interaction (MMI) or as ‘frequency lock-in’ (FLI), depending on the number of mode(s) of the structure contributing to the interaction. If the structural response does show vibration of a single mode only, thereby resulting in a near-harmonic structural response, the vibration is classified as ‘frequency lock-in’.

Once multiple modes are present in the structural response, the vibration is classified as multi-modal interaction. As time series of multi-modal interaction can vary significantly, we further extend their classification by a numeral, indicating the dominant structural mode, e.g., MMI-I in the case of major periodicity in the load and response signals being around the period of the first structural mode.

One important point here is that for an SDOF oscillator, commonly used in numerical analysis and model testing, the response during continuous brittle crushing will show periodicity around the first and only eigenmode. The difference with frequency lock-in is then only observable by a fluctuating amplitude of response, by looking if periodicity in the ice load exists, or by checking the amplitude of structural response.

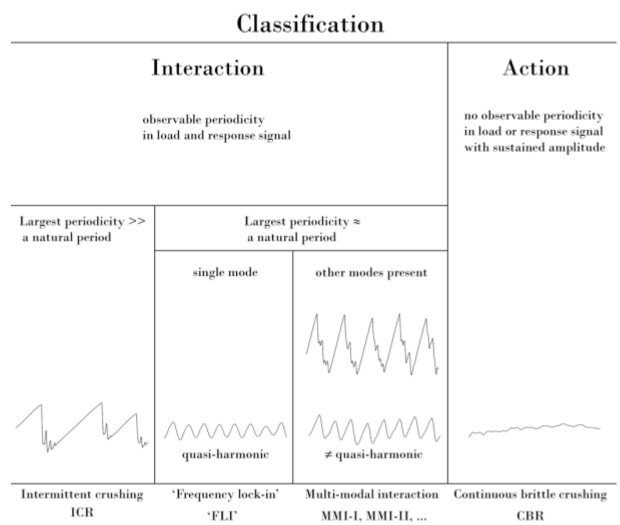

FIGURE 7: THE CLASSIFICATION SCHEME FOR ICE-INDUCED VIBRATION BASED ON OBSERVABLE PERIODICITY IN THE STRUCTURAL RESPONSE AT THE ICE ACTION POINT. NO PERIODICITY IS CLASSIFIED AS ICE ACTION OR CONTINUOUS BRITTLE CRUSHING, WHILE SIGNALS WITH ANY PERIODICITY ARE CLASSIFIED AS ICE-STRUCTURE INTERACTION. ICE-STRUCTURE INTERACTION CAN BE SUB-DIVIDED IN INTERMITTENT CRUSHING, ‘FREQUENCY LOCK-IN’ OR MULTI-MODAL INTERACTION BASED ON FREQUENCY CONTENT OF THE RESPONSE SIGNALS.

4. DISCUSSION

In this chapter we will discuss three examples of application of the proposed classification scheme and reflect on the observed findings with respect to the interaction of ice with offshore wind support structures during the experiments and their implications for design.

4.1 Sustained vibrations during constant speed tests

To check for robustness, we applied the proposed classification scheme to eight different time series of structural displacements, measured during the test campaign (Figure 8). As the lowest ice drift speed (here 0.005 m s^{-1}) clearly indicates a main periodicity larger than the first eigenfrequency, it can be classified as ICR (a).

Ice drift speeds of 0.010 m s^{-1} – 0.020 m s^{-1} indicate vibrations close to the first eigenmode. As the second and third eigenmode are present as well, observed vibrations can be classified as MMI-I (b).

For an ice drift speed of 0.025 m s^{-1}, time series still indicate periodicity, now close to the second eigenmode. As the third mode is present, the vibration can be classified as MMI-II (c). As the third eigenmode, for an ice drift speed of 0.030 m s^{-1}, even can become dominant, we here classified the vibration cycles as MMI-III (d).

We note that the ice-induced vibration types of MMI-II and MMI-III seem to compete in this range of ice drift speeds. For the highest ice drift speed, phases of no apparent periodicity are recognizable. Here phases of ice-induced vibrations are classified as CBR (e). For the vibration patterns of the higher ice drift speed tests, only examples of ice-induced vibrations have been marked as the system would change between CBR and different types of interaction.

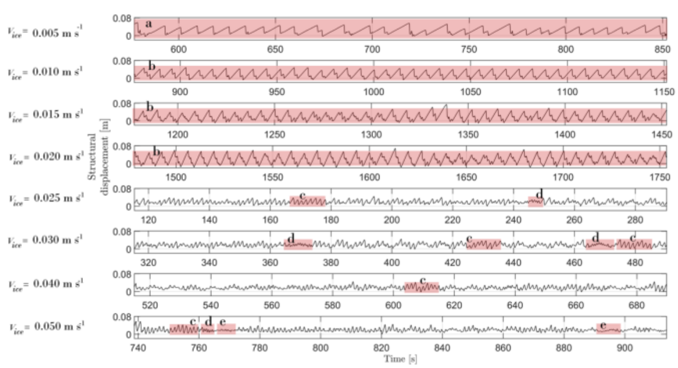

FIGURE 8: OPERATIONAL TURBINE, 90-DEGREE MISALIGNMENT, (TEST 387-390; 405-408, 631). THE CLASSIFICATION SCHEME ALLOWS TO CLASSIFY MEASURED ICE-INDUCED VIBRATIONS FOR AN OPERATIONAL TURBINE UNDER 90-DEGREES MISALIGNED LOAD SCENARIO, ONLY BASED ON THE PERIODICITY OF RESPONSE SIGNALS. FOR HIGHER ICE DRIFT SPEEDS, ONLY SOME EXAMPLES OF ICE-INDUCED VIBRATIONS HAVE BEEN MARKED.

4.2 Vibrations during constant deceleration of ice

Results from a test of an idling offshore wind turbine interacting with a constantly decelerating ice floe are shown in Figure 9. The test concerns a constantly decelerating ice floe changing its speed from 80 mm s^{-1} to 0 mm s^{-1} resulting in different types of structural responses as representatively shown by the ice load, structural displacement, and wavelet plot of structural displacement.

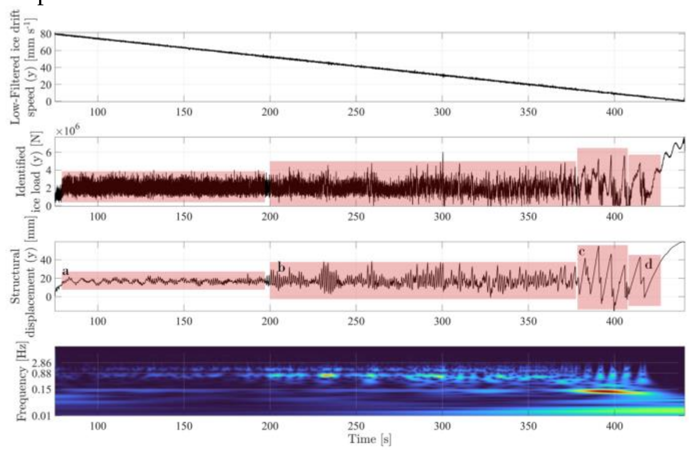

FIGURE 9: IDLING TURBINE (TEST 589). TOP PLOT: THE ICE DRIFT SPEED (HERE: CARRIAGE SPEED) HAS BEEN LOW-PASS FILTERED (25 HZ, BUTTERWORTH). SECOND PLOT: THE ICE LOAD SCALED BACK TO FULL-SCALE. THIRD AND FOURTH PLOTS: THE STRUCTURAL DISPLACEMENT AND CORRESPONDING WAVELET PLOT. GLOBAL BENDING MODES OF THE STRUCTURE ARE INDICATED IN THE WAVELET PLOT BY 0.15 HZ, 0.88 HZ AND 2.86 HZ TICK MARKS.

Once the carriage starts to move, first mode vibrations of the structure occur (Figure 9 (a)). This could be classified as one of the interaction scenarios; however, these vibrations are obviously caused by start-up effects / initial conditions. This shows one of the cases where classification purely based on time series of response at the ice action point is not possible and some more information of the scenario is required.

With decreasing ice drift speed, periodic vibrations start to occur (b). As these vibrations are close to the second eigenfrequency and we also see other modes contributing, these are classified as multi-modal interaction, here dominated by the second eigenmode (MMI-II). For lower ice drift speeds, we notice that the dominant periodicity changes to one close to the first structural mode (c). Again, we do see a second periodicity close to that of the second eigen period, especially during phases of structural reversal. Hence, the regime can be classified as multi-modal interaction, dominated by the first eigenmode (MMI-I).

For lowest ice drift speeds, we notice that the main response frequency shifts down to a frequency below the first eigenfrequency, which is why we classified the last cycle as intermittent crushing (d), though without the information of the whole time series such classification of a single cycle is challenging.

Analysis of the frequency spectra, here provided in the form of a wavelet plot, or analysis of relative velocities between the ice and structure (as presented in Figures 4-6), can help to confirm the classification. Still, as ice velocities are typically not measured directly during instances of ice-induced vibrations in full-scale, classification should ideally be based on the structural response.

4.3 Transient vibration

A last example is used to show that the classification of ice-induced vibrations is best based on time series and not on statistical measures of such time series. One reason for that are the initial vibrations, as explained in Section 4.2, which can influence the statistical measures. A second reason is that changes in the ice sheet itself can significantly influence the resulting ice-induced vibrations. A change of the ice thickness, for example, can lead to a different failure mode of the ice (e.g., bending instead of crushing). Also, a short distance of thicker ice can change the interaction; hence, the type of ice-induced vibration.

As an example of both these types of influences, Figure 10 shows the structural displacement and global ice load for an operational turbine in a 30-degree misaligned scenario, influenced by initial vibrations and change of ice properties during the test. The periodicity of the time series shows that MMI-II first develops after transient initial vibrations of the structure have decayed (a). This type of interaction is followed by 1-2 cycles of intermittent crushing (b). The reason for that was a larger ice thickness during testing, resulting from one of the water nozzles malfunctioned during the ice spraying process. After the large load drop, some MMI-I-cycles develop as a transient scenario when the ice thickness decreased again (c). MMI-II is not yet reached at the end of the signal, though it is expected that if the test were continued this equilibrium would have reinstated itself.

An analysis of such a time series based on statistical measures of the complete signal would lead to misinterpretation of the interaction.

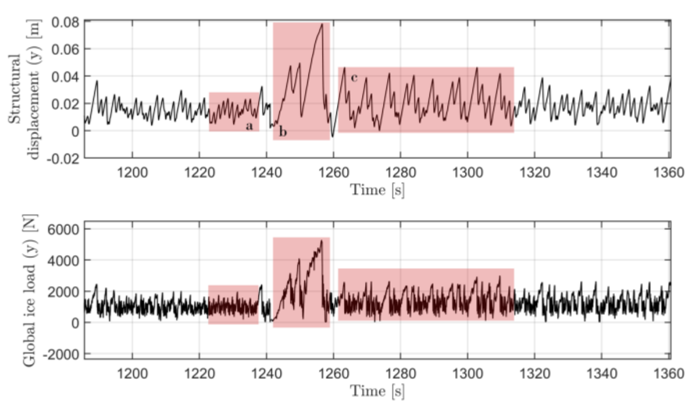

FIGURE 10: THE STRUCTURAL DISPLACEMENT AND GLOBAL ICE LOAD OF AN OPERATIONAL TURBINE AT 0.015 M S^{-1}, SHOWS THE INFLUENCE OF INITIAL VIBRATIONS AND INITIAL CONDITIONS ON THE DEVELOPMENT OF ICE-INDUCED VIBRATIONS.

4.4 Design

The experimental data showed that ice-induced vibrations of offshore wind turbines cannot be accurately described by common terminology in literature and design guidelines. This may pose a risk for design of offshore wind turbines as the emphasis is currently on a type of interaction (‘frequency lock-in’) not necessarily most relevant for design. In a recent study, it was shown that the multi-modal interaction is likely to govern the support structure design when ice is considered [9]. An update of terminology is therefore warranted to which the attempt at classification in this paper is a first step.

Ice-induced vibrations develop as a consequence of a specific combination of ice and structure properties [15]. Periods of low relative velocity seem to govern the development of high load peaks which are otherwise absent from the ice load signal. Though different vibration patterns of the structure are observed for different ice drift speeds, these all develop likely due to the same mechanism(s).

It does matter a lot how the structural properties relate to the ice properties. A very heavy and stiff structure will just show continuous brittle crushing in mild ice conditions. It is therefore not appropriate to discuss ice-induced vibrations in terms of regimes with specific boundary velocities as done for frequency lock-in in the ISO standard. Such boundary velocities are only indicative for the structures from which these were derived, in the ice conditions at the time of observation. What can be said is that in general these are the low ice drift speeds which are most likely to result in significant ice-structure interaction.

The definitions of intermittent crushing and continuous brittle crushing currently used in the standards can be applied to offshore wind turbines. At the lowest of ice drift speeds an interaction characterized by saw-tooth load and displacement signals develops with a periodicity much larger than the first natural period of the structure (intermittent crushing). At the highest ice speeds, the ice load becomes stochastic around a mean value with high frequency content. Neither the ice load nor the structural response indicates any meaningful form of periodicity as the ice does not significantly interact with the structure (continuous brittle crushing).

What happens in between these low and high speeds is most interesting from the perspective of the design of the structure and this is where existing terminology fails for offshore wind turbines. ‘Frequency lock-in’ suggests a single mode of oscillation of the structure dominating the response, which is not the case for the wind turbines due to their dynamic characteristics which cause the second and third global bending modes to be easily excited by the ice. The response is not harmonic when the multi-modal interaction develops (Figures 3 and 4).

Besides this observation, there is more to say about the term ‘frequency lock-in’ which suggests that the ice and structure possess a characteristic frequency which synchronizes in time. This is far from reality as the frequency content of the ice load in absence of the structure shows no specific dominant frequency. The term was originally introduced based on a proposed similarity between ice-induced vibrations and vortex-induced vibrations, with the difference that vortex shedding around a stationary cylinder does show an inherent periodicity.

In our opinion it would be better to drop the term ‘frequency lock-in’ and replace it by something better reflecting the problem considered. As there is no consensus yet about the physical mechanisms behind ice-induced vibrations, we will refrain from introducing a new term and use quotation marks for 'frequency lock-in' instead.

In the context of the wind turbine results presented here, we found two types of amplified ice-induced vibrations (Figure 11). The first type, the most significant for ULS design, is characterized by a first mode dominated saw-tooth response with second and third mode contributions in the unloading phase. The second type, which most resembles the old 'frequency lock-in' definition, is characterized by a multi-modal interaction of the second and third mode.

It is noted that as we tested a model of a large state-of-the-art wind turbine the third mode is easily excited by the ice. For older, smaller turbines, the third mode contribution may be absent which would result in 'frequency lock-in' in the second mode to more resemble the classical observations on 'frequency lock-in'.

Adopting classification as proposed here in the existing design standards for offshore wind turbines allows to emphasize the importance of the multi-modal interaction for the design.

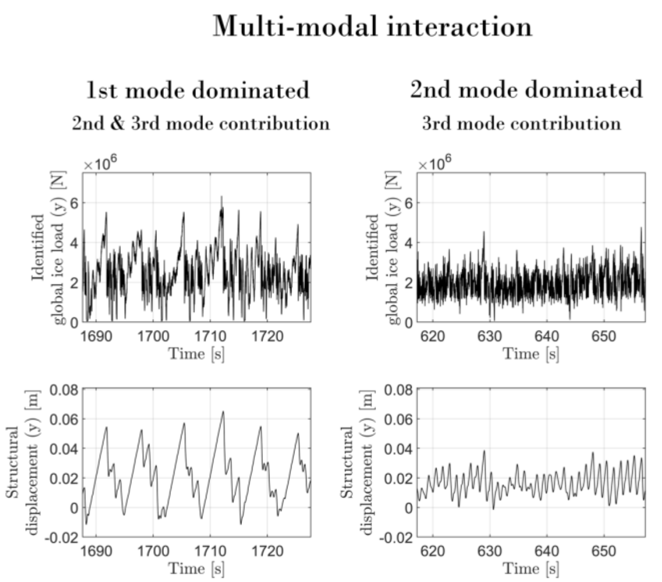

FIGURE 11: MULTI-MODAL INTERACTION BETWEEN FLOATING LEVEL ICE AND OFFSHORE WIND TURBINES CAN BE EXPECTED TO GOVERN DESIGN ICE LOADS.

5. CONCLUSION

This paper summarized experimental findings of importance for the design of offshore wind turbines in sub-arctic regions. Ice-induced vibrations defined as intermittent crushing, multi-modal interaction, and continuous brittle crushing have been observed. It is recommended to update design guidelines to explicitly account for multi-modal interaction between ice and structure as it yields the largest bending moments in parts of the monopile foundation. The results further illustrate that 'frequency lock-in' is not typically observed for a large offshore wind turbine due to its specific dynamic properties at the ice action point.

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