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Analytical assessment of sea ice-induced frequency lock-in for offshore wind turbine monopiles

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A B S T R A C T

In this paper, an analytical method is presented to assess FLI (Frequency lock-in) of monopile support structures for offshore wind turbines, subjected to loading by floating sea ice. The method is introduced, justified and presented with an example. The main idea of the method is to use existing knowledge regarding structural response velocities at which FLI can occur. Using such velocities, the structural response can be determined easily when single mode response is assumed, which is a conservative choice when analyzing FLI.

The method is particularly useful for early stages of the design process, when the implication of ice loads on the design needs to be assessed without time-consuming simulations. Results from the method can also be used to identify structural configurations which are most critical for ice loading.

1. Introduction

Offshore wind energy is increasingly successful, in particular across Europe. Most offshore turbines are supported by monopiles, with diameter currently around 6 m (at the waterline) to more than 8 m within the seabed. The support structure is assessed for fatigue (FLS) and extreme (ULS) conditions according to IEC 61400-3-1 [2].

In ice infested waters, sea ice needs to be considered for both FLS and ULS load cases; the corresponding load case table is shown as Table 1. Different mechanisms and loading regimes are relevant for the assessment of ice loads and ice-induced vibrations [3]. This paper focusses on assessment of one particular type of ice-induced vibrations being frequency lock-in (FLI) for offshore wind turbines (OWT) supported by monopiles. These are relatively soft structures, natural frequencies for typical 6–8 MW turbines are in the order of $f_0 = 0.20 \ldots 0.25$ Hz. Future larger turbines with >10 MW will most likely show frequencies significantly below this range. This particular combination of structural properties makes these structures susceptible to structural vibrations as a result of frequency lock-in, at least based on recent theoretical and experimental work [3]. Full-scale data to confirm this is, however, not available due to the lack of existing structures with similar properties.

FLI is relevant for load cases D3, D4 (during production) and D7, D8 (during idling) according to IEC 61400-3-1 where moving ice at different velocities is considered. It is industry practice to determine time series of ice forces, which are an input to the wind turbine manufacturer's simulation model. Such ice force time series are provided by ice experts, who typically use simplified, or phenomenological, models to account for ice-structure-interaction. Single-degree-of-freedom (SDOF) models with generalized (modal) properties are used to represent the real structure.

Time domain simulations are cumbersome, mainly because of the interaction process between ice expert and wind turbine

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Symbols and abbreviations

f_n	Natural frequency of mode n [Hz]
h	Ice thickness [m]
q	Fraction of peak force for sawtooth time series [-]
t	Time [s]
u_t	Structural response displacement amplitude [m]
v_{ice}	Ice drift velocity [m/s]
v_t	Structural response velocity [m/s]
$v_{t,\max}$	Maximum structural response velocity [m/s]
z	Height along the structure ($z = 0$ m is at MSL) [m]
z_n	Modal (generalized) coordinates [m]
DAF_n	Dynamic Amplification Factor of mode n; $DAF_n = 1/(2\xi_n)$ [-]
F	Ice force [N]
F_{mean}	Mean global ice load [N]
$F_{\max}$	Maximum value of ice force (termed "action" in ISO 19906) [N]
$F_{\min}$	Minimum value of ice force (termed "action" in ISO 19906) [N]
ΔF	Difference between maximum and minimum values of ice force [N]
$F_{gen,n}$	Generalized force of mode n [N]
K_n	Generalized stiffness of mode n [N/m]
K_s	Structural static stiffness at the ice force point [N/m]
M_n	Generalized mass of mode n [kg]
$M_{res,n}(z)$	Bending moment for normalized mode shape of mode n [Nm/m]
M_{dyn}	Bending moment induced by dynamic ice force [Nm]
$M_{ice,mean}$	Bending moment induced by mean (average) ice force [Nm]
M_{ULS}	Maximum bending moment governing ULS of the structure [Nm]
V_{hub}	Wind speed at hub height [m/s]
V_{out}	Cut-out wind speed at hub height [m/s]
EWM	Extreme wind speed model
FLS	Fatigue Limit State
MSL	Mean Sea Level
NTM	Normal turbulence model
NWLR	Normal water level range
SRV	Structural Response Velocity
ULS	Ultimate Limit State
β	Factor between 1.0 and 1.5 [-]
ξ_n	Modal damping ratio of mode n [-]
$\Phi_n(z)$	Mode shape of mode n [-]
$\Phi_{n,MSL}$	Modal amplitude of mode n at the ice force point (assumed to be MSL) [-]
ω_n	Natural frequency of mode n [rad/s]
Θ	Coefficient with suggested value of $\Theta = 40 \cdot 10^6 \frac{kg}{ms}$ [kg/ms]

manufacturer, see Ref. [12]. Additionally, the uncoupled approach does not necessarily result in a conservative design as the ice loads are strongly dependent on the structural motions during the interaction. Purpose of this paper is therefore to present a simplified method to assess FLI without the need for time domain simulations. Such method can be applied to obtain valuable insight during the design process. During conceptual design, it can be used to estimate load levels induced by FLI and during basic/detailed design it is helpful to identify scenarios which are design driving and need to be investigated with more sophisticated models.

Table 1
Design load cases for sea/lake ice according to IEC 61400-3-1 Ed. 1 [2].

Design situation	DLC	Ice condition	Wind condition	Water level	Type of analysis	Partial safety factor
Power production	D1	Horizontal load from temperature fluctuations	NTM $V_{hub} = V_r \pm 2$ m/s and V_{out} Wind speed resulting in maximum thrust	NWLR	U	N
	D2	Horizontal load from water level fluctuations or arch effects	NTM $V_{hub} = V_r \pm 2$ m/s and V_{out} Wind speed resulting in maximum thrust	NWLR	U	N
	D3	Horizontal load from moving ice at relevant velocities $h = h_{50}$ or largest value of moving ice.	NTM $V_{in} < V_{hub} < V_{out}$	NWLR	U	N
	D4	Horizontal load from moving ice at relevant velocities *Use values of h corresponding to expected history of moving ice occurring.*	$V_{in} < V_{hub} < V_{out}$	NWLR	F	*
	D5	Vertical force from fast ice covers due to water level fluctuations	No wind load applied	NWLR	U	N
Parked	D6	Pressure from hummocked ice and ice ridges	EWM Turbulent wind model $V_{hub} = V_1$	NWLR	U	N
	D7	Horizontal load from moving ice at relevant velocities *Use values of h corresponding to expected history of moving ice occurring.*	NTM $V_{hub} < 0{,}7\ V_{ref}$	NWLR	F	*
	D8	Horizontal load from moving ice at relevant velocities $h = h_{50}$ or largest value of moving ice.	EWM Turbulent wind model $V_{hub} = V_1$	NWLR	U	N

Simplified approaches exist (such as ISO19906 [1]), however these are still requiring time domain simulations and an iterative procedure and their applicability for wind turbines is uncertain. The approach presented in this paper is much simpler and only requires modal analysis to be carried out numerically. All other steps can be executed in a spreadsheet.

In Section 2 we present general characteristics of the interaction between ice and structure during frequency lock-in which forms the basis of the developed method. In Section 3 and 4 the method is presented with subsections describing the different steps in detail. Section 5 provides a calculation example. In Section 6 results are discussed and options for detailed calculation of the interaction are given.

2. Frequency lock-in

Frequency lock-in of vertically sided structures subjected to level ice crushing has resulted in consistent observations in experimental and full-scale measurement campaigns in the past [4,8,10,11]. An example of a typical structural displacement, structural velocity, and global ice load signal are shown in Fig. 1. The response and load signal shown here have been obtained with a numerical model [7]. For comparison to an experimentally obtained signal with similar characteristics, see Figure 11 in Ref. [14]. If frequency lock-in develops the structure undergoes a close to harmonic oscillation at a frequency often equal or slightly smaller than one of the natural frequencies of the structure. The time dependence of the structural velocity and global ice load show that the deviation from harmonic oscillation occurs around the time the structure starts to move back towards the ice and this motion is briefly resisted by the ice. The amplitude of structural velocity has been first found to be typically in the range of 1.0 up to 1.5 times the ice velocity by Toyama et al. [8] and later confirmed in other experimental campaigns. Based on these observations the structural displacement signal during frequency lock-in can be approximated by:

$$u_t(t) = \frac{F_{mean}}{K_s} + \frac{\beta \cdot v_{ice}}{\omega_n} \cdot \sin(\omega_n \cdot t) \tag{1}$$

with $u_t(t)$ Structural displacement at the ice force point, F_{mean} Mean global ice load, K_s Structural stiffness at the ice force point, β Factor between 1.0 and 1.5, v_{ice} Ice drift velocity, ω_n Natural frequency of the mode in which FLI has developed, t Time.

3. Analytical method basics

Past experience has shown that assessment of FLI is not straightforward, mainly due to the fact that uncoupled models are used – an ice load model which is owned by the ice expert and a wind turbine simulation model, which is owned by the wind turbine manufacturer. As FLI is an ice-structure-interaction phenomenon, creating time series with a simplified single degree-of-freedom (SDOF) model and applying this to a more complex model of the wind turbine with its support structure can lead to non-physical results. Therefore, having a simplified method is preferred. If such an assessment shows unacceptable levels of fatigue damage induced by FLI, or shows that FLI might be critical for ULS conditions, then more refined methods have to be used to assess this in more detail. Such more refined approaches are discussed in Section 6.

The main objective of the method proposed here is to avoid time domain simulations and the iterative process which results from the simplified method given in ISO 19906, section A.8.2.6.1.5. This iterative procedure is replaced by an inverse approach, whereby the structural response estimation on the basis of Eq. (1) is an input to the procedure.

The proposed method is based on the following main considerations:

- FLI only occurs for certain ice speeds and the structural response velocity (SRV) is then close to the ice speed. Hence, a certain SRV can be assumed as an upper bound estimate. This SRV is an input for the method and it is discussed in section 3.4.
- Based on the SRV at MSL, structural response can be determined per mode considered. This is done by assuming that the structure vibrates in one mode only with the SRV at MSL given. The amplitudes of structural displacement and acceleration for the full

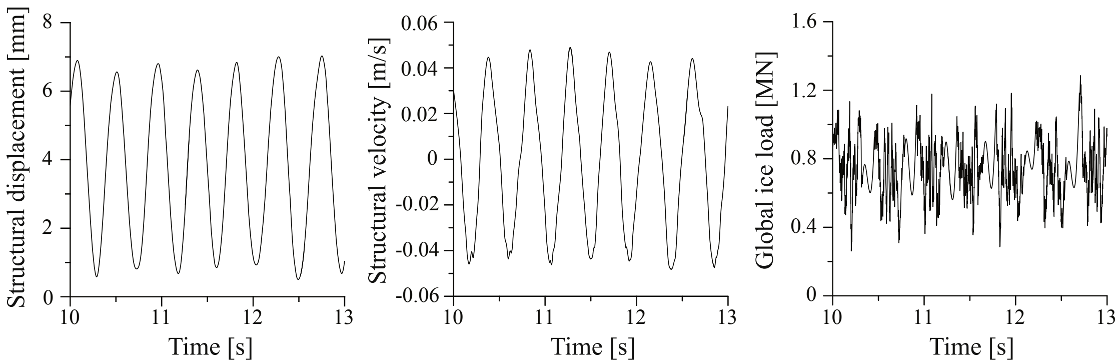

Fig. 1. Typical (simulated, using the model in Ref. [7]) structural displacement, structural velocity, and global ice load during frequency lock-in of a structure with a natural frequency of 2.32 Hz at an ice drift velocity of 0.04 m/s.

structure can then be easily calculated.

- Whether such response can actually be excited by the ice forces can be estimated from the saw tooth forcing function according to ISO 19906 (Figure A.8-23). For a harmonic motion, the first Fourier component is used as input, assuming linear system behaviour. If the maximum SRV can't be excited, then the response is limited to the forced vibration amplitude. This is checked by applying the ice load function, calculating the response and then comparing with the SRV determined from the ice velocity upper limit.

The required steps are shown in Fig. 2 and further explained in the following sections.

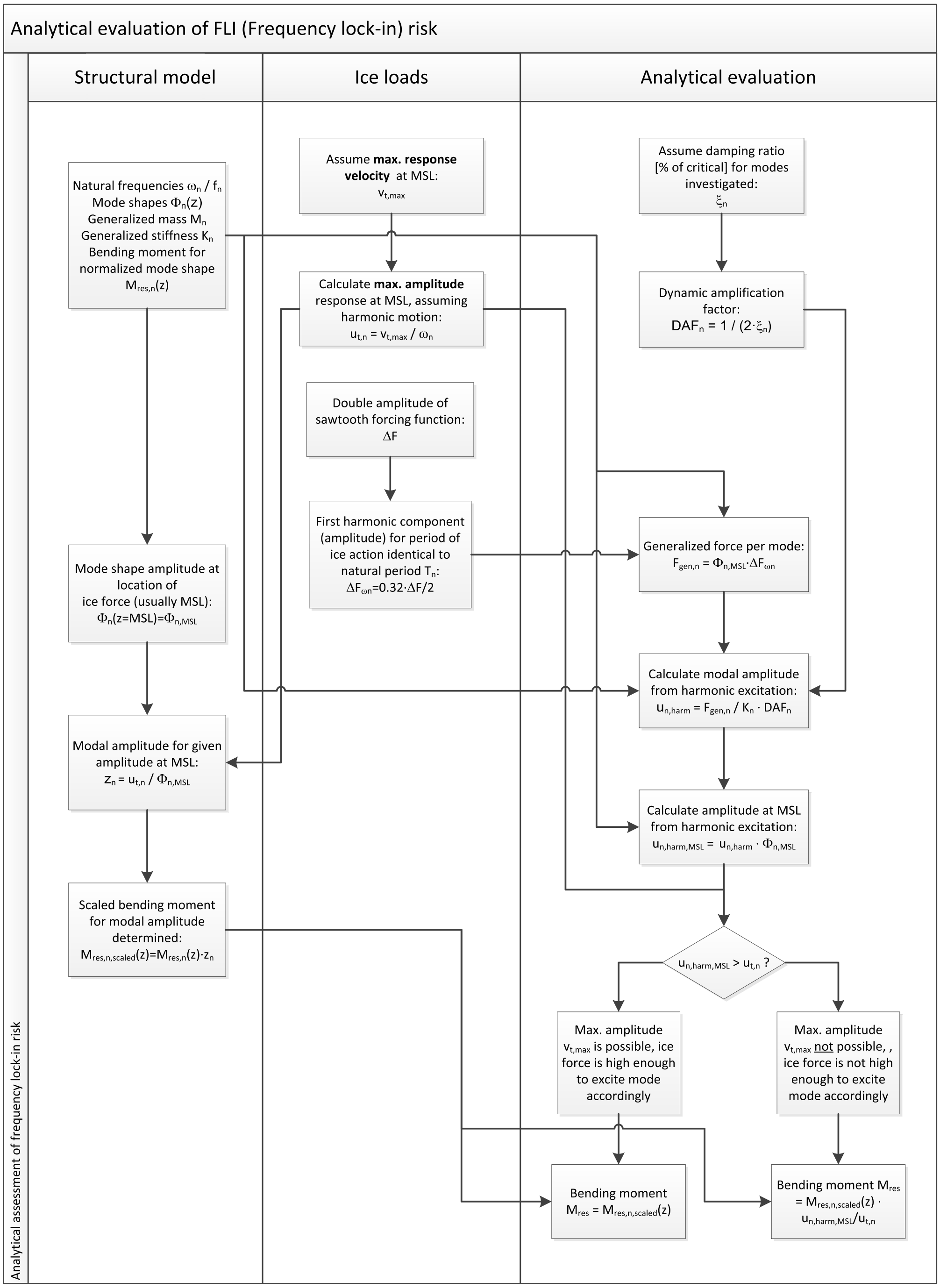

Fig. 2. Flow-chart for proposed analytical method.

It can be noted that the method can be used in two different ways:

i. Based on the predicted maximum ice velocity, the maximum structural response can be obtained. Bending moments along the structure are calculated based on the maximum structural response displacement amplitude at water level. Bending moments obtained can be used for structural assessment purposes, both FLS and ULS.
ii. Alternatively, the maximum ice velocities expected at the investigated site, can be compared with "allowable" ice velocities, which are inversely calculated based on allowable structural response, for which bending moments are still acceptable.

The first approach is the more natural approach taken by structural designers, while ice experts may find the second approach useful as this provides insight into when moving ice actually becomes critical for a given structure.

3.1. Step 1: Obtain input from modal analysis

Equations of motion are described as follows:

$$\underline{m}\cdot\underline{\ddot{y}}(t) + \underline{d}\cdot\underline{\dot{y}}(t) + \underline{k}\cdot\underline{y}(t) = \underline{f}(t) \tag{2}$$

The structural model of the structure is built in a Finite Element (FE) (beam) model and the following system properties are obtained:

$$\underline{m} \quad \text{Mass matrix} \tag{3}$$

$$\underline{k} \quad \text{Stiffness matrix} \tag{4}$$

$$\underline{d} \quad \text{Damping matrix} \tag{5}$$

Mode shapes $\underline{\Phi}_n(z)$ (eigenvectors) are determined which satisfy the following equation:

$$(\underline{k} - \omega^2\cdot\underline{m})\cdot\underline{\Phi} = 0 \tag{6}$$

This is a step which is assumed to be known to the reader, as this is standard methodology in structural dynamics. Details can e.g. be found in Ref. [13].

The equations of motion can be described using modal coordinates z(t), i.e. the displacement vector is written as a linear combination of mode shape vectors:

$$\underline{y}(t) = \underline{\Phi}\cdot\underline{z}(t) \tag{7}$$

$$\underline{\Phi}^T\cdot\underline{m}\cdot\underline{\Phi}\cdot\underline{\ddot{z}}(t) + \underline{\Phi}^T\cdot\underline{d}\cdot\underline{\Phi}\cdot\underline{\dot{z}}(t) + \underline{\Phi}^T\cdot\underline{k}\cdot\underline{\Phi}\cdot\underline{z}(t) = \underline{\Phi}^T\cdot\underline{f}(t) \tag{8}$$

Generalized (modal) properties are calculated as:

$$\underline{M} = \underline{\Phi}^T\cdot\underline{m}\cdot\underline{\Phi} \quad \text{Generalized mass matrix} \tag{9}$$

$$\underline{K} = \underline{\Phi}^T\cdot\underline{k}\cdot\underline{\Phi} \quad \text{Generalized stiffness matrix} \tag{10}$$

$\underline{M}$ and $\underline{K}$ are diagonal matrices with generalized mass M_n and generalized stiffness K_n per mode n on the main diagonal.

The equations of motion can be uncoupled in case of damping being assumed in terms of modal damping ratios and response in each mode is given by a single degree of freedom (SDOF) system:

$$\ddot{z}_n(t) + 2\cdot\xi_n\cdot\omega_n\cdot\dot{z}_n(t) + \omega_n{}^2\cdot z_n(t) = \frac{1}{M_n}\cdot F(t) \tag{11}$$

For harmonic loading, the solution can be expressed using a Dynamic Amplification Factor (DAF), which is the factor of dynamic response divided by quasi-static response. At resonance, the response amplitude is then:

$$z_{\max} = \frac{\Delta F/2}{K_n}\cdot\frac{1}{2\xi_n} = \frac{\Delta F/2}{K_n}\cdot DAF_n \tag{12}$$

Modal damping ratios ξ_n must be determined; these are usually estimated based on experience.

When mode shape and natural frequency are known, then the bending moment distribution along the structure can be determined from the nodal displacements and element stiffness matrices (or alternatively by integrating mass multiplied with accelerations along the structure). The mode shape is non-dimensional, hence the bending moments have a unit of [Nm/m].

When loading the structure, the generalized force vector is determined as:

$$\underline{F}(t) = \underline{\Phi}^T\cdot\underline{f}(t) \tag{13}$$

The following quantities are hence determined for each mode:

a. Natural frequencies $\omega_n = 2\cdot\pi\cdot f_n$ (14)

b. Mode shapes $\Phi_n(z)$ – normalized to "1" at maximum deflection (15)

The mode shape amplitude at location of ice force (usually MSL) is of particular relevance

$$\Phi_n\ (z\ =\ MSL)\ =\ \Phi_{n,MSL} \tag{16}$$

c. Generalized mass M_n (17)

d. Generalized stiffness K_n (18)

e. Bending moment for normalized mode shape $M_{res,n}(z)$ (19)

f. Modal damping ratios ξ_n (20)

3.2. Step 2: Ice force input and response due to ice load

Ice forces are determined according to ISO 19906 (see Fig. 3):

a. Estimates of the global ice load $F_{\max}$ are obtained based on formula A.8-21 in ISO 19906
b. Estimate fraction q of peak force for sawtooth – conservatively, $q = 0.5$ is used here, as this is the upper bound given in ISO 19906
c. Determine mean (average) ice load F_{mean}, harmonic force component ΔF and generalized force $F_{gen,n}$

It is noted here that the representative ULS ice load based on ISO19906 equations A.8-21 results in maximum loads to be expected during continuous brittle crushing. In order to obtain the mean load level during frequency lock-in this load has to be reduced, although direct use of the maximum value results in a conservative approach.

The sawtooth can be represented by a Fourier sine series as follows, neglecting the mean value:

$$x(t) = \sum_{n=1}^{\infty} b_n \cdot \sin(n \cdot \omega_0 \cdot t) \tag{21}$$

$$b_n = -\frac{\Delta F}{\pi \cdot n} \cdot (-1)^n \tag{22}$$

The comparison to the original sawtooth function using 17 harmonics is shown in Fig. 4. This is included here for illustration that the Fourier series indeed sums up to a sawtooth pattern. The number of 17 harmonics has been arbitrarily selected.

For the excitation of one of the lowest modes of a monopile, the first harmonic component is relevant and its amplitude is determined as:

$$b_1 = \frac{\Delta F}{\pi} = 0.318 \cdot A \tag{23}$$

Based on this, the forced response can be determined as follows, assuming linear system behaviour:

1) Determine the difference between maximum and minimum value of ice force. According to ISO 19906, this can conservatively be taken as 50% of the max. ice force.

$$\Delta F = 0.5 \cdot F_{\max} \tag{24}$$

For each of the considered occurrences of ice thickness and ice strength considered in the FLI analysis the max force is determined from ISO19906 equations A.8-21.

2) Determine the harmonic force amplitude

$$\Delta F_{\omega n} = 0.32 \cdot \Delta F = 0.32 \cdot 0.50 \cdot F_{\max} = 0.16 \cdot F_{\max} \tag{25}$$

3) Determine the generalized force, which excites the system, as.

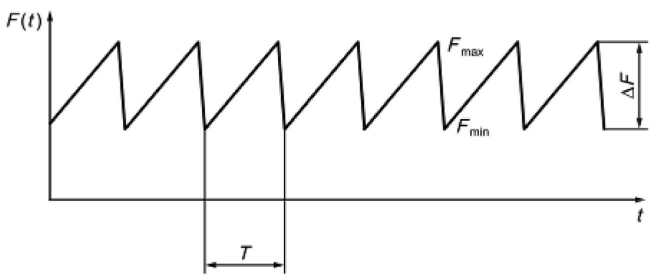

Fig. 3. Sawtooth forcing function from ISO 19906 (Figure A.8–23).

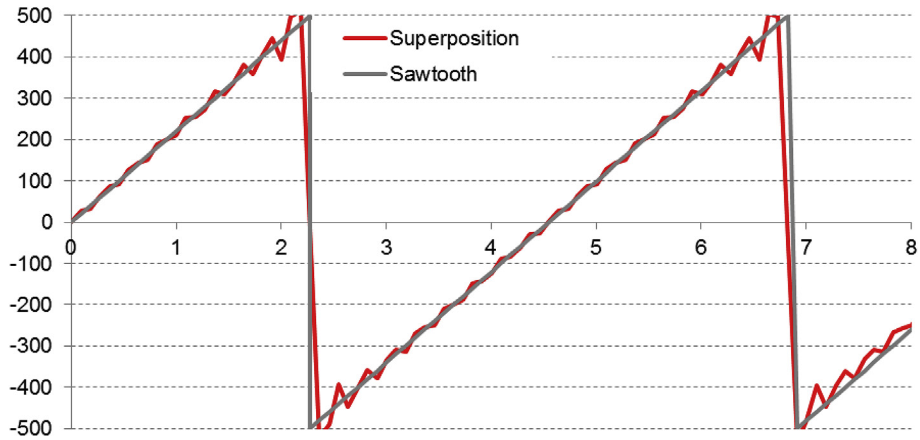

Fig. 4. Sawtooth time series and superposition of harmonics.

$$F_{gen,n} = \Phi_{n,MSL} \cdot \Delta F_{\omega n} \tag{26}$$

This follows directly from Eq. (13), as the load is only applied at one elevation and then the vector product becomes a scalar product of the mode shape at the point of load application multiplied with the load.

4) The harmonic response amplitude triggered by such harmonic generalized force depends on stiffness and damping. Assuming the damping ratio ξ_n for each mode, the harmonic response can be determined as.

$$u_{n,harm} = \frac{F_{gen,n}}{K_n} \cdot \frac{1}{2\xi_n} = \frac{F_{gen,n}}{K_n} \cdot DAF_n \tag{27}$$

Later, the maximum response for the assumed velocity (Step 4) and the maximum possible response from the forcing function can be compared. The smaller value is assumed governing for this particular ice force magnitude.

3.3. Step 3: Check ISO 19906 susceptibility criterion

For the assessment of the modes susceptible to frequency lock-in we rely on the empirical formula presented in ISO 19906 [1] which describes the stability of the mode:

$$\xi_n \geq \frac{{\Phi_{n,MSL}}^2}{4 \cdot \pi \cdot f_n \cdot M_n} \cdot h \cdot \Theta \tag{28}$$

with ξ_n Structural damping of mode n as a fraction of critical, $\Phi_{n,MSL}$ Modal amplitude of mode n at the ice force point, f_n Natural frequency of mode n, M_n Modal mass, h Ice thickness, Θ Coefficient with suggested value of 40^*10^6 [kg/ms].

Based on the given equation all modes which are vulnerable to frequency lock-in can be identified. There are some concerns with respect to the empirical coefficient Θ and its range of applicability. We therefore advise to consider any mode for which the inequality Eq. (28) results in a relatively small difference between the right-hand side and left-hand side. This is in particular the case for modes with low damping.

The output of this step is the modes susceptible to frequency lock-in.

3.4. Step 4: Bending moments for estimated maximum structural response velocity (SRV)

Once the susceptible modes have been identified it is required to estimate the range of ice drift velocities for which frequency lock-in can develop in the ice conditions considered. Currently the only way to do this is based on experience or simplified numerical simulation. In a separate paper [9] we have given a detailed argument as to the application of estimation formulas from literature and numerical modelling for this particular purpose. Here we present our current approach based on results presented in Ref. [9]. This step is analyzed for ice conditions representative of ULS conditions. This requires the determination of representative ice load which can be done based on ISO19906 equations A.8-21 [1]. Modal properties required are obtained from Step 1.

Provided that the maximum response velocity is triggered by the ice force signal, bending moments for that situation can be easily determined. This will be used later, but is explained here because it is directly related to the velocity input.

Steps required are:

1) Maximum ice velocity: The value of $v_{\text{ice}} = 0.06$ m/s for the first mode and $v_{\text{ice}} = 0.10$ m/s for the higher modes is suggested in Ref. [9] as an initial estimate for moderate ice climates in the southern Baltic Sea.

2) The maximum structural response velocity is estimated as:

$$v_{t,\max} = \beta \cdot v_{ice} \tag{29}$$

with $\beta = 1.4$ according to ISO19906.

3) Assuming harmonic response of the structure, the structural response displacement amplitude can be calculated from the structural response velocity as:

$$u_{t,n} = v_{t,\max}/\omega_n \tag{30}$$

This is the (maximum) response amplitude at MSL.

4) Assuming response in one mode only, the modal amplitude can be determined for each mode considered:

$$z_n = u_{t,n}/\Phi_{n,MSL} \tag{31}$$

5) The bending moment for harmonic motion with such a modal amplitude follows directly from the bending moment for the normalized mode shape:

$$M_{res,n,scaled} = z_n \cdot M_{res,n} \tag{32}$$

This is the maximum bending moment that can occur when FLI is fully developed and harmonic motion occurs for a constant ice speed/structural response velocity.

4. Design assessment

In the previous steps data has been generated which is input to ULS (Ultimate Limit State) and FLS (Fatigue Limit State) design checks. The data can be used in different ways, and two possibilities are applied in the following: An inversed procedure, based on checking critical velocities, for ULS and direct computation of FLI induced bending moments based on force and velocity for FLS.

4.1. Step 5: ULS criticality check

For the assessment of the structural effect of frequency lock-in on ULS we apply an inverse procedure, in which the velocities creating critical ULS load levels are determined. Each of the susceptible modes is analyzed separately. The ice drift velocity which would result in ULS conditions for the structure is obtained as follows:

a Determine the maximum bending moment governing ULS of the structure: M_{ULS} This is the maximum bending moment from all other load cases according to IEC 61400-3-1. Safety factors need to be included, but are omitted here for clarity. Usually, it is sufficient to consider bending moments at some locations, e.g. interface, MSL and mudline.
b Determine bending moment from mean ice load: $M_{ice,mean}$ The bending moment from mean ice load is calculated as quasi-static moment, based on the point of application and lever arm to location considered.
c Determine bending moment which should not be exceeded by dynamic ice force:

$$M_{dyn} = M_{ULS} - M_{ice,mean} \tag{33}$$

d Find the corresponding ice velocity for frequency lock-in for which that dynamic moment is not exceeded. This is done by reversing the steps described in section 3.4: The modal amplitude resulting in the critical bending moment is calculated and the corresponding velocity amplitude follows.

If the thus obtained velocity per mode is significantly larger than the expected range of velocities for that specific mode the ULS criterion will be satisfied. If the obtained velocity is in the range or close to the range of ice drift velocities determined there is a need for a detailed analysis. Methods for such detailed analysis are discussed in Section 6.

Alternatively, the same procedure as described in Step 6 can be applied to determine bending moments from assumed ice drift velocities, from which bending moments are calculated for ULS design checks.

4.2. Step 6: FLS assessment input

Frequency lock-in can only develop at a certain ice drift velocity if the ice force is of sufficient magnitude to provide the energy necessary for sustained oscillation of the structure. The values for ULS ice force conditions per mode have been determined in Step 2.

These values govern the maximum velocity range at the highest load level. For a fatigue study the occurrence of different ice thickness and ice strength combinations results in different load levels. For each of those the maximum velocity for lock-in will be different from that obtained for ULS conditions.

For each possible ice drift velocity, the maximum response velocity is estimated as:

$$v_{t,\max} = \beta \cdot v_{ice} \tag{34}$$

with $\beta = 1.4$ according to ISO 19906.

The “sawtooth” forcing function from ISO 19906 (Fig. 3) is used as input to determine the maximum velocity at which frequency lock-in can develop in a given mode for an ice force level resulting from a specific combination of ice thickness and ice strength. This is considered to be a quite conservative approach, delivering an upper bound of possible response.

The maximum velocity is governing and the bending moments resulting from such a response are used as input for FLS assessment.

A flow-chart visualizing the entire process to determine bending moments is given in Fig. 2.

4.3. Step 7: Fatigue damage evaluation

Fatigue damage needs to be evaluated based on occurrence probabilities for different ice conditions and assumptions on occurrence of FLI. It is generally accepted that FLI does not always occur when the ice conditions theoretically predict FLI. Bjerkås [6] discusses a method how to determine the number of vibration cycles from FLI, although it needs to be evaluated whether the lighthouse example used is representative enough for offshore wind turbines, as it is a stiff structure and the number of cycles based on this might underpredict what happens for flexible wind turbines.

The study of occurrence probabilities of ice conditions (e.g. thickness, strength), ice drift velocities, and intervals, or duration, of ice drift is generally obtained from consultants or ice experts and falls outside of the scope of this paper. Once a probability matrix has been obtained it can be transformed into a matrix of occurrence of ice load level vs. ice drift velocity with given durations. This can be used for an initial fatigue assessment.

The simplest and perhaps extremely conservative approach is to assume frequency lock-in to always occur for all ice load levels and all susceptible modes at velocities in the range as determined in step 4. Disregarding the mean displacement component in Eq. (1) the stress amplitudes can be directly calculated from the oscillation pattern of the structure, as described in the previous section.

If the hence obtained fatigue damage shows to be significant a second iteration can be made refining the range of velocities for which FLI can develop given different load levels. It is theoretically understood that the lower the global load level the lower the maximum velocity at which FLI can develop. In our analysis we have so far only used the ULS load level to determine the velocity range where frequency lock-in develops. Once for each load level the range of velocities has been determined a more detailed fatigue damage evaluation can be made.

If the latter evaluation still predicts significant impact of frequency lock-in to the fatigue of the structure a detailed analysis is required. Especially the effect of consideration of all modes combined can reduce the determined fatigue damage significantly, as for a single velocity only a single mode can lock-in. Methods for detailed analysis are further discussed in Section 6.

A note is made that FLI is not the only condition which contributes to structural fatigue. The development of a type of interaction known as intermittent crushing, commonly associated with low ice drift velocities, and the low amplitude response as a result of continuous brittle crushing, commonly associated with high ice drift velocities, also contribute to the total fatigue. These regimes are not considered as part of this work. For continuous brittle crushing simplified approaches have been proposed in Ref. [15]. For intermittent crushing the best method is currently the use of simulations.

5. Example

5.1. Input parameters

The following input is assumed for the example:

- Design ice thickness: 0.40 m
- Support structure geometry is not included here in detail – only relevant results, like natural frequencies and mode shape amplitudes, are given.
- The determination of the maximum ice force is not further elaborated in this paper. It has been calculated as: $F_{\max} = 2287 kN$, this value is also used for the ULS check.

5.2. Bending moments induced by FLI

Results are shown for the first four modes in Table 2.

The mode shapes for the structure used as an example in this paper are plotted in Fig. 5. The corresponding bending moment distributions [MNm/m] are shown in Fig. 6. Those must be interpreted as follows: If the structure vibrates with the mode shapes as in Fig. 5, with the maximum amplitude equal to 1 m (e.g. at the top of the structure for mode 1), then the bending moment as presented in Fig. 6 occurs.

Table 2
Results for example.

Mode No.		1	2	3	4
Step 1: Input from modal analysis					
Natural frequency f_n	[Hz]	0.226	0.626	1.546	1.709
Circular frequency ω_n	[1/s]	1.42	3.93	9.71	10.74
Generalized stiffness K_n	[MN/m]	1.24	44	58.9	59.1
Generalized mass M_n	[t]	615	2850	624	513
Circular frequency (check based on K_n and M_n)	[1/s]	1.42	3.93	9.72	10.73
Damping ratio ξ	[%]	1	1	1	1
DAF	[-]	50	50	50	50
Modal amplitude @ MSL	[-]	0.147	-0.854	-0.008	0.059
Modal amplitude @ HH	[-]	1.000	0.777	0.042	-0.124
Modal amplitude @ Mudline	[-]	0.033	-0.293	0.131	-0.138
Moment @ MSL for normalized mode shape	[MNm/m]	120.1	428.7	706.9	691.5
Moment @ Mudline for normalized mode shape	[MNm/m]	204.3	774.3	769.6	1002.3
Step 2: Ice force input					
Max. ice force (LC E.3) F_{max}	[kN]	2287	2287	2287	2287
Fraction q of peak force for sawtooth	[-]	0.5	0.5	0.5	0.5
Mean ice load F_{mean}	[MN]	1.71	1.71	1.71	1.71
Harmonic force (amplitude) $\Delta F\omega n$	[kN]	366	366	366	366
Generalized force $F_{gen,n}$	[kN]	53.6	312.6	2.9	21.7
Step 3: ISO 19906 susceptibility criterion					
ISO criterion: $\xi_{n,min}$	[%]	20%	52%	0.01%	0.5%
Actual damping ratio ξ_n	[%]	1%	1%	1%	1%
FLI possible according to ISO 19906 ?		**Yes**	**Yes**	**No**	**No**
Step 4: Velocity input					
Max. ice velocity v_{ice}	[m/s]	0.06	0.1	0.1	0.1
$\beta = v_{t,max} / v_{ice}$	[-]	1.4	1.4	1.4	1.4
Max. response velocity at MSL $v_{t,max}$	[m/s]	0.084	0.140	0.140	0.140
Step 5: ULS criticality check					
MSL:					
Quasi-static bending moment (from mean ice load)	[MNm]	0	0	0	0
ULS design moment	[MNm]	200	200	200	200
Resonse amplitude @ MSL for ULS moment at MSL	[m]	0.244	0.399	0.002	0.017
Response velocity @ MSL for ULS moment at MSL	[m/s]	0.346	1.568	0.022	0.184
Mudline:					
Quasi-static bending moment (from mean ice load)	[MNm]	77.2	77.2	77.2	77.2
ULS design moment	[MNm]	500	500	500	500
Resonse amplitude @ MSL for ULS moment at mudline	[m]	0.30	0.47	0.00	0.03
Response velocity @ MSL for ULS moment at mudline	[m/s]	0.43	1.84	0.04	0.27

(continued on next page)

Table 2 (*continued*)

Step 6: FLS assessment input					
Max. amplitude @ MSL = $v_{t,max}$ / ω	[m]	0.0592	0.036	0.014	0.013
Max. amplitude @ HH - scaled based on mode shape	[m]	0.404	-0.032	-0.077	-0.027
Max. amplitude @ Mudline - scaled based on mode shape	[m]	0.013	0.012	-0.239	-0.030
Modal amplitude z	[m]	0.404	0.042	1.824	0.220
Bending moments for vibration with modal amplitude z:					
Moment @ MSL - scaled from modal amplitude	[MNm]	48.5	17.9	1289.6	152.0
Moment @ Mudline	[MNm]	82.5	32.3	1404.0	220.4
Max. amplitudes based on ice force input:					
Modal amplitude (max.)	[m]	2.165	0.355	0.002	0.018
Amplitude @ MSL from harmonic force	[m]	0.317	0.303	0.000	0.001
Amplitude @ MSL from assumed max. velocity	[m]	0.059	0.036	0.014	0.013
Is the ice force high enough to excite the max. velocity?		**Possible**	**Possible**	**Not possible**	**Not possible**
Scaled moment (amplitudes) for fatigue assessment					
Moment @ MSL	[MNm]	48.5	17.9	1.73	12.7
Moment @ Mudline	[MNm]	82.5	32.3	1.89	18.4

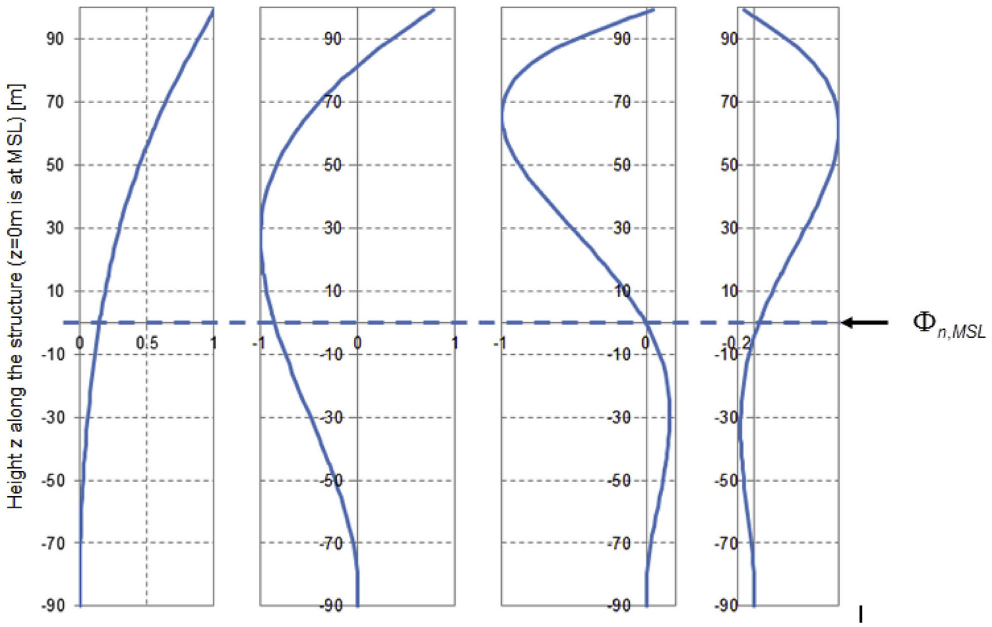

Fig. 5. Mode shapes for the first modes with lowest natural frequencies.

Some remarks on intermediate steps:

Step 1:

- Generalized stiffness and mass and for mode shapes normalized to "1" at maximum deflection. For the first mode, this leads to easily interpreted results: The generalized stiffness is approximately equal to the quasi-static stiffness for a force applied at hub height and the generalized mass is RNA mass plus part of the support structure mass (often RNA mass +10 … 15% of the support structure mass is used as an approximation).

Step 2:

- Mean ice load is computed from max. ice load and sawtooth amplitude and results to 75% of maximum load.
- Harmonic force is: $\Delta F_{\omega 1} = 0.16 \cdot F_{\max} = 0.16 \cdot 2287 = 366\ kN$
- Generalized force is: $F_{gen,1} = \phi_{1,MSL} \cdot \Delta F_{\omega 1} = 0.147 \cdot 366 = 53.6\ kN$

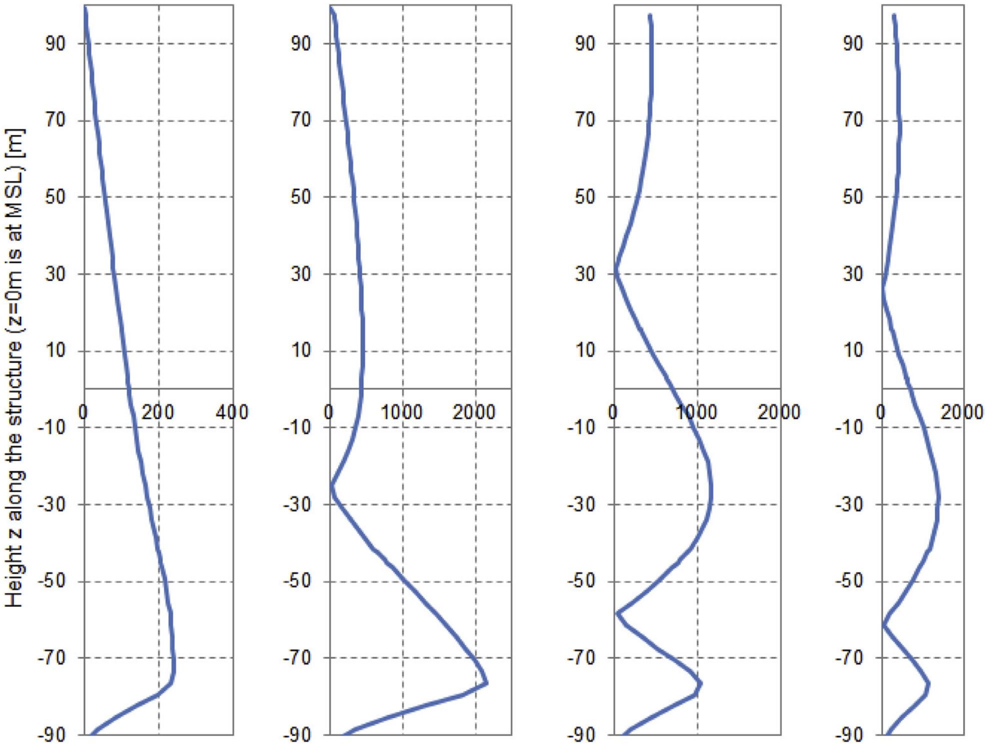

Fig. 6. Bending moments (absolute values) for the first modes.

Step 4:

- Max. ice velocity: The value of 0.06 m/s for the first mode and 0.10 m/s for the higher modes is suggested in Ref. [9] for moderate ice climates in the southern Baltic Sea, with ice thickness not exceeding 0.5 m and an ice load level given by a C_R value of 1.0.

Step 5:

- Moments at MSL and mudline for normalized mode shape are taken from the modal analysis.
- Quasi-static bending moment from mean ice load at MSL is Zero, as this is the point of load application. Below MSL, a linear increase is assumed.
- ULS design bending moments of 200MNm at MSL and 500MNm as mudline as used as examples here.
- In order to arrive at 200MNm bending moment at MSL, the following response amplitude is required for the first mode:
  - Response amplitude at maximum deflection is calculated from the moment at MSL of the normalized mode shape, which is 120.1MNm for 1 m deflection. Hence, the maximum amplitude for 200MNm at MSL follows from linear scaling: $u_{\max} = 200/120.1 = 1.665m$
  - Response amplitude at MSL is then calculated by scaling with the modal amplitude: $u_{MSL} = 0.147 \cdot 1.665 = 0.244m$
  - The resulting velocity of $v_{MSL} = \omega \cdot u_{MSL} = 1.42 \cdot 1/s \cdot 0.244m = 0.35m/s$ for this amplitude (at 0.226 Hz frequency) is well above reasonable velocities for FLI. Hence, ULS can be assessed as non-critical in this case.
- For the third mode, only a very small amplitude of 0.002 m is required to generate 200MNm moment amplitude. This is because of the very small mode shape amplitude $\Phi_{3,MSL} = 0.008$. But this mode has already been excluded from being critical based on the ISO criterion in Step 3, which is confirmed by the calculations in Step 6, which show that only a very small bending moment can actually be excited by the ice force.

Step 6:

The response based on the assumed max. response velocity is calculated first:

- Maximum amplitude at MSL for first mode: $u_{t,1} = v_{t,\max}/\omega_1 = \frac{0.084m/s}{1.42\,1/s} = 0.059m$
- Modal amplitude: $z_1 = u_{t,1}/\Phi_{1,MSL} = 0.0592m/0.147 = 0.404m$
- Scaled bending moment: $M_{res,1,scaled} = 0.404m \cdot 120.1MNm/m = 48.5MNm$

This can be compared with the forced amplitude:

- Response based on ice force input: $u_{1,harm} = \frac{F_{gen,1}}{K_1} \cdot \frac{1}{2\xi_1} = \frac{53.6 \cdot 10^{-3}MN}{1.24MN/m} \cdot 50 = 2.16m$
- Amplitude at MSL hence: $u_{1,MSL} = 2.16m \cdot 0.147 = 0.317m$

For FLS, it can be seen that the amplitude that can be excited by the harmonic force (0.317 m) is much larger than the assumed amplitude (0.059 m) for the first mode. The resulting bending moment is not very large, hence it may be possible to demonstrate low fatigue utilization from FLI, even when making conservative assumptions on occurrence. If this is not the case, then more detailed investigations are necessary.

It can be seen from Table 2 that Mode 1 and 2 can be excited to 8.4 cm/s or 14 cm/s response velocity respectively, bending moments are moderate to low. Mode 3 and 4 can't be excited to 14 cm/s, as the ice force is too low to create such large movements. From Ref. [9] it is also found that for mode 3 and 4 frequency lock-in is not possible.

5.3. Sensitivity studies

The presented model can also be used to conduct sensitivity studies to identify the most onerous situations for FLI. Generally, uncertainty exists in particular regarding soil stiffness, which impacts natural frequencies and mode shapes. Mode shapes are particularly relevant here, because structural motion velocities and generalized forces depend on the mode shape value at MSL. As a first approximation, it can e.g. be assumed that soil stiffness impacts mode shape amplitude more than natural frequency and the latter can be kept constant while the mode shape amplitude is varied. At the same time, damping ratios can be varied and then maximum bending moments can be determined.

For the first mode (Table 3), maximum moments increase when the mode shape amplitude at MSL decreases. For a damping ratio of 1.0%, the maximum moment is obtained for a multiplier of ~0.40.

For the third mode (Table 4), maximum moment increases when the mode shape at MSL increases. For a damping ratio of 1.0%, the maximum moment is obtained for a multiplier of ~30. Such an increase would require significantly different soil properties, which would also affect natural frequency, hence this result is only indicative.

It is hence found that stiffer soil can be more onerous for FLI compared to soft soil. Usually, soft soil is governing for offshore wind turbine loads, as then wave excitation is higher. For FLI, this is not the case, because of the following mechanism: By assuming the SRV at MSL, the response velocity at hub height is inversely proportional to the mode shape amplitude at MSL, see Eq. (31). Hence, a smaller mode shape amplitude creates larger amplitudes at hub height and larger moments. This mechanism is limited by the amplitude which can be excited by the ice force, as generalized stiffness - Eq. (18) - increases and generalized force decreases, Eq. (26). Both items lead to a decrease in forced amplitude, Eq. (27). Hence, the response for FLI will increase until the limit in forced amplitude is reached.

For the first mode, the ice force is high enough to excite the maximum response velocity. Even if the generalized force decreases (for small mode shape amplitudes), this is still the case and higher velocities at hub height with corresponding higher bending moments are induced.

Table 3
Maximum bending moments for the first mode depending on damping ratio [%] and mode shape multiplier at MSL. Note that colour codes are per line, i.e. highest values per damping ratios are marked in red.

First mode	Mode shape multiplier									
Damping ratio	0.1	0.2	0.3	0.4	0.5	0.6	0.8	1.0	2.0	5.0
0.5	35	70	96	72	58	48	36	29	14	6
1.0	18	35	53	70	58	48	36	29	14	6
1.5	12	23	35	47	58	48	36	29	14	6
2.0	9	18	26	35	44	48	36	29	14	6
2.5	7	14	21	28	35	42	36	29	14	6
3.0	6	12	18	23	29	35	36	29	14	6
3.5	5	10	15	20	25	30	36	29	14	6
4.0	4	9	13	18	22	26	35	29	14	6
4.5	4	8	12	16	20	23	31	29	14	6
5.0	4	7	11	14	18	21	28	29	14	6

Table 4
Maximum bending moments for the third mode depending on damping ratio [%] and mode shape multiplier at MSL. Note that colour codes are per line, i.e. highest values per damping ratios are marked in red.

Third mode	Mode shape multiplier									
Damping	1.0	5.0	10.0	20.0	30.0	40.0	50.0	60.0	70.0	80.0
0.5	2	12	24	46	31	23	18	15	13	12
1.0	1	6	12	24	31	23	18	15	13	12
1.5	1	4	8	16	24	23	18	15	13	12
2.0	1	3	6	12	18	23	18	15	13	12
2.5	0	2	5	9	14	19	18	15	13	12
3.0	0	2	4	8	12	16	18	15	13	12
3.5	0	2	3	7	10	13	17	15	13	12
4.0	0	1	3	6	9	12	15	15	13	12
4.5	0	1	3	5	8	10	13	15	13	12
5.0	0	1	2	5	7	9	12	14	13	12

For the third mode, the modal amplitude at MSL is so small that no significant global response can be excited. Hence, for increased modal amplitude at MSL, larger response will occur.

It can be further observed that the most severe case shifts to larger mode shape multipliers with increased damping. This can be explained by the larger forces that are necessary to excite the structure to maximum SRV when damping increases. Therefore larger modal amplitudes at MSL are required to achieve the necessary level of generalized forces.

More detailed studies can easily done with the analytical model and complete information about mode shapes and frequencies, e.g. by changing soil stiffness input, and potentially critical configurations can be identified. Achieving the same with time domain simulations would be a very cumbersome process, which is not practical.

6. Summary and discussion

In this paper, an analytical method has been presented to assess FLI (Frequency lock-in) of monopile support structures for offshore wind turbines.

The proposed method assumes response in a single mode only, which is not necessarily correct. It is anticipated that multi-mode response, which can be assessed with a coupled analysis model only, will lead to less conservative, more accurate, results, because FLI is less likely to develop when different modes are interacting.

The method is considered to give an upper bound estimate of the effect FLI may have for ULS and FLS conditions. In the different steps of the method the choices, for example the maximum velocity and ratio between structure and ice drift velocity, are made such that the most severe situation occurs, from the perspective of structural response.

The approach can be considered of comparable accuracy to detailed modelling, when in the detailed modelling the structure is simplified to a single-degree-of-freedom oscillator. For more complex structural representations detailed modelling will give more realistic responses and the amount of frequency lock-in cases and modes in which it develops will likely be less than given by the method in this article. The challenge is in obtaining a proper estimate of the velocities for which FLI will develop given specific ice conditions. If that is done using state-of-the-art models, the accuracy of this approach will be good. Validation of the approach itself is difficult, but the underlying theory and numerical modelling have recently been validated in model-scale results of which will be published in due time. Full-scale validation is ongoing, but is as for all ice models challenging given the little data available.

The method is particularly useful for early stages of the design phase, when the implication of ice loads on the design need to be assessed without time-consuming simulations. Results from the method can also be used to identify structural configurations which are most critical for ice loading. Unlike for wave induced loads, where usually the softest configuration is governing, stiffer configurations might be more onerous for FLI.

During detailed design, more advanced models, ideally directly coupled with the wind turbine simulation model, should be used. The majorities of models which can be applied for this purpose are phenomenological and require careful application for new structures, such as offshore wind turbines, which have structural properties outside of the range of experience from lighthouses and offshore platforms. There is no consensus amongst researchers about the actual mechanism governing the development of ice-induced vibrations resulting in a large scatter in predictions. Our argument for the use of the model in Ref. [7] is given in detail in Ref. [3]. So far it is the only model which captures the main trends in existing observations.

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