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A MODEL TEST ON ICE-INDUCED VIBRATIONS: STRUCTURE RESPONSE CHARACTERISTICS AND SCALING OF THE LOCK-IN PHENOMENON

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ABSTRACT

Ice-induced vibrations of offshore structures have been a serious issue for engineers since the discovery of the problem as early as in the late 1960's. Despite considerable research efforts and experiences since then, the problem is not completely understood. In order to further investigate this problem, a collaboration had been initiated between National University of Singapore (NUS) and Dalian University of Technology (DUT) to conduct a model test study on ice-induced vibrations, utilizing existing test facilities at DUT. A model jacket structure with variable indentor sizes and saline ice sheets of variable ice thicknesses was used in the current study.

The current study successfully replicated various ice-induced vibration modes ranging from low to high indentation velocities. The test parameters are varied in such a way that the characteristics of the various vibration modes can be traced in a consistent manner, allowing a closer look at the transition between distinct vibration modes which up to now have had to be limited to qualitative descriptions of these modes. The results show that the vibration modes leading to, and departing from the lock-in mode can be described by a combination of the ratio of average structure vibration velocity amplitude to ice velocity, and another ratio representing the variability of the structure vibration displacement amplitudes. This provides a basis for characterizing the lock-in vibration mode. Finally, it is shown that dimensionless parameters can be relevant in describing the lock-in phenomenon and in relating its occurrences across small-scale and full-scale structures.

INTRODUCTION

Serious research activities in ice engineering began in the 1960s driven by the need to venture offshore into ice-infested waters for oil and gas. Closely tied with the oil and gas development, high crude oil prices from the 1970s to early 1980s further helped intensify research activities until the prices eventually settled in the late 1980s. In recent years research activities have again gathered pace due to various reasons, e.g. for fear of supply disruptions, depletion of existing oil and gas fields, etc. Steady progress has been made throughout the years in ice engineering and related studies, however, this field of study remains comparatively immature compared to other well-established subjects such as hydrodynamics and thermodynamics.

The current understanding on ice-induced vibrations of structures, similarly, remains incomplete. A model test study devised to investigate the mechanics of ice-induced vibrations is described in this paper. Lock-in vibration, where the structure vibrates at one of its lower natural frequencies with near uniform displacement amplitudes, is the focus for the current study since it almost always represents the most damaging ice-induced vibration mode.

MODEL TEST

With the objective to investigate the mechanics of ice-induced structural vibration, a model test study was initiated between National University of Singapore (NUS) and Dalian University of Technology (DUT) in 2010 utilizing existing test facilities at DUT. The existing test facilities were used in previous studies carried out by DUT in which the model structure was treated as a scaled model of typical Bohai Sea jacket structures (Yue et al., 2006; Guo et al., 2007). It should be noted that the current test study differs from the previous studies in that the current test was devised to be an investigation of the more fundamental nature which examines ice-induced structural vibration, instead of one that is intended to relate information between a model structure and a prototype structure according to commonly adopted scaling laws.

During testing a sheet of non-floating saline ice is pushed at a constant velocity against an indentor sitting atop the model structure (Figure 1). Another type of common test arrangement involves pushing a non-submerged model structure or compliance simulator against a sheet of stationary floating ice. Neither type of test arrangement accounts for the effects of water added mass and hydrodynamic damping since the model structure is not submerged in water.

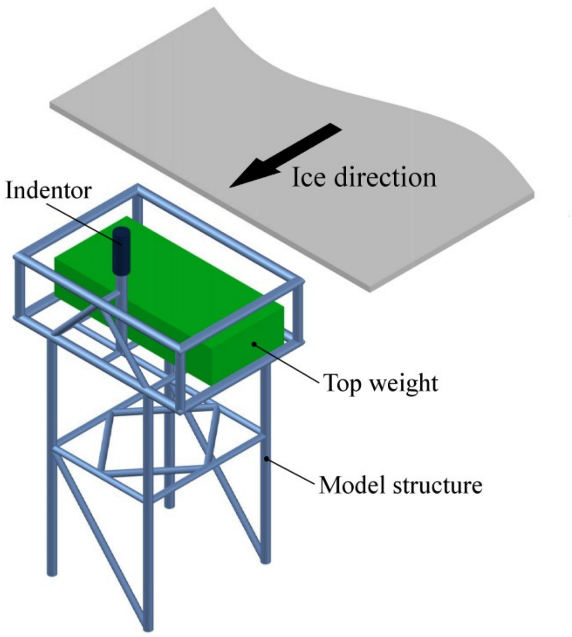

Figure 1. Current test arrangement schematic.

The current experimental setup is as shown in Figure 2: A saline ice sheet with an average salinity of 7‰ is grown in an ice mould sitting on a carriage supported by a steel frame, the bottom-founded model structure is instrumented with displacement transducers and strain gauges, and the movement of the ice carriage is controlled by a hydraulic actuator. The cold chamber that houses the sheet ice and model structure measures approximately 5.5 m long x 3.3 m wide x 4.7 m tall.

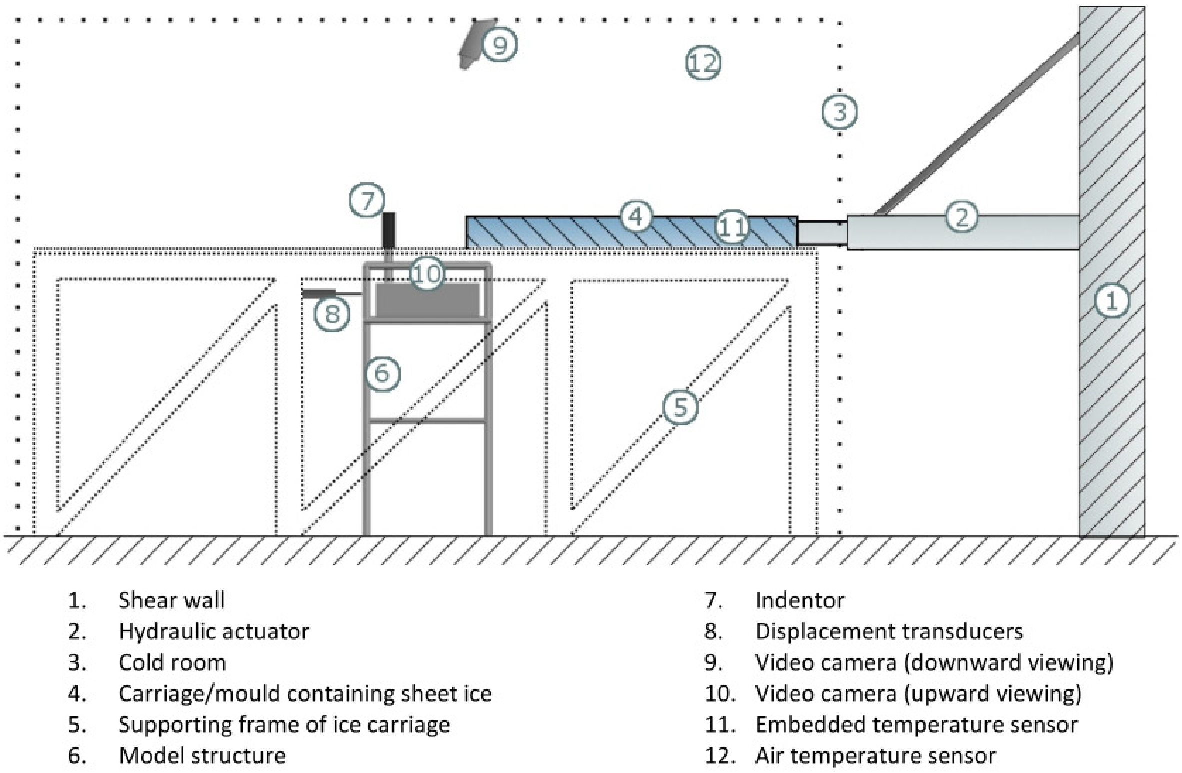

Figure 2. Experimental setup schematic.

Saline sheet ice with thicknesses *h* of 25 mm and 50 mm were used in the current study. A fabric study conducted on thin sections made from these sheet ice indicate that the structure of the ice is transitional, between that of columnar and frazil ice[1]. The average brine pocket array spacing of these sheet ice was estimated to be approximately 0.5 mm, consistent with the range between 0.4 mm to 1 mm found in the High Arctic first year sea ice (Nakawo and Sinha, 1984). The ice fabric diagrams covering a total of 817 ice grains are given in Figure 3, and the microstructure of a typical horizontal thin section is shown in Figure 4. The average ice salinity was approximately 7‰.

The model structure has a lowest natural frequency of 2.3 Hz in the ice direction, a stiffness of 690 kN/m and a damping ratio of 0.01. Two indentor with diameters *W* of 80 mm and 120 mm were used, giving a range of aspect ratios *W/h* between 1.6 to 4.8. The four sets of test configurations with various indentor diameter and ice thickness combinations are given in Table 1. A total of 28 tests were conducted and the test results were obtained with ice velocities ranging from 2 mm/s to 80 mm/s; constant velocities were maintained during each test. The air and ice temperatures were kept at approximately -5˚C during testing. A detailed account of the model test study can be found in Yap (2011).

[1] Frazil ice is a newly-formed ice feature that is needle- or plate-like in appearance.

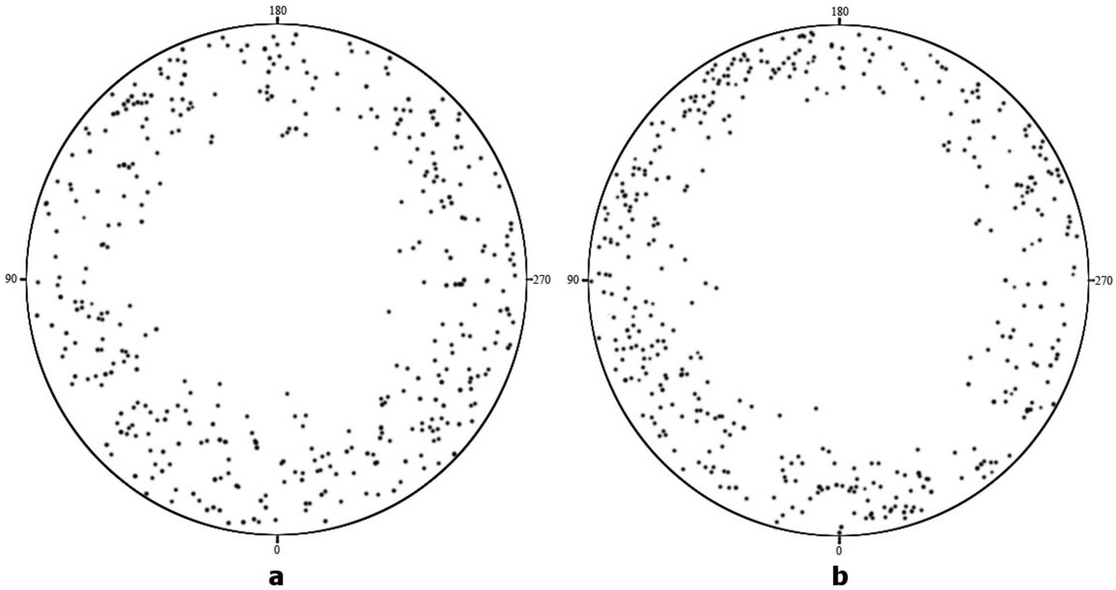

Figure 3. Ice fabric diagrams for current test study (a: 25mm-thick ice; b: 50mm-thick ice).

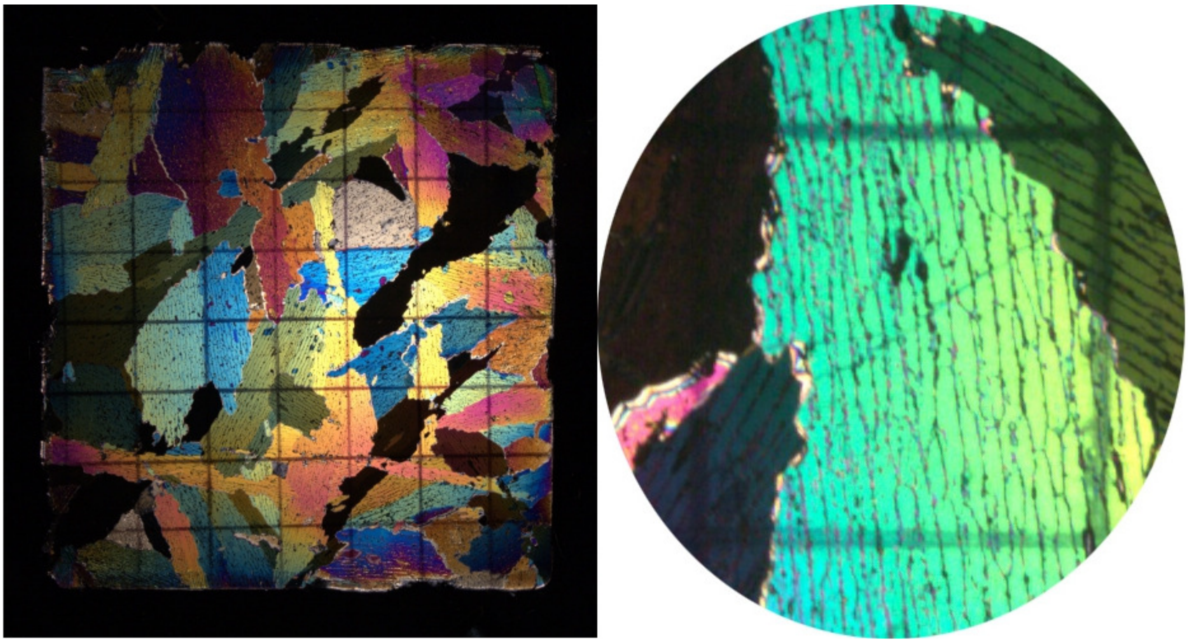
Figure 4. Sheet ice microstructure in current test study (viewed under cross-polarized light on a centimetre grid).

Table 1. Current test study configurations.

Test Configuration	**Indentor Diameter *W* (mm)**	**Ice Thickness *h* (mm)**
1	80	50
2	120	50
3	80	25
4	120	25

ICE VELOCITY EFFECT

When an ice floe moves against a structure, it pushes the structure in the direction it is moving – the period of time when the structure moves in the direction of ice is generally termed a ‘loading phase’. The ice in contact with the structure eventually fails and the structure springs back in the opposite direction, crushing and extruding some distance of ice on its way – the period of time when the structure moves in the opposite ice direction is generally termed an ‘unloading phase’. The ice floe continually pushes the structure thereby setting it into motion, and in turn the motion of the structure plays an important part in the interaction – depending on the rate the ice is moving, the characteristics of the motions can be distinctly different.

Based on observations of this process, the various ice-induced structural vibration modes are commonly categorized into four typical types according to the structure vibration characteristics (ISO, 2010; Karna, 1990; Palmer et al., 2010; Sodhi and Haehnel, 2003; Yue et al., 2009; etc.). These are, in reference to Figure 5:

Creep: Ice creeps at very low ice velocities, e.g. during thermal expansion of an ice sheet. The ice force is at a much lower level compared with other modes.

Quasi-static: At low ice velocities, ice force builds up slowly as the structure deflects. A precipitate drop in force follows failure of the ice causing the structure to springs back in the opposite ice direction, and contact with the ice is slowly established again after some periods of structure oscillation.

Lock-in: Within a certain range of ice velocities, a condition of frequency lock-in can occur. During lock-in, the structure vibrates at one of its lowest natural frequencies with near uniform vibration amplitudes.

Random vibration: At high ice velocities, continuous crushing of the ice occurs throughout the entire interaction event. The structure vibrates in a chaotic manner around a mean deflection.

It should be noted that the above descriptions have had to be confined to qualitative treatments due to our incomplete understanding of the interaction processes; of the three vibration modes which are usually of engineering interest (except creep), it can often be difficult to differentiate one mode from another, and different terminologies are often used by different researchers (see Palmer et al. (2010) for a review).

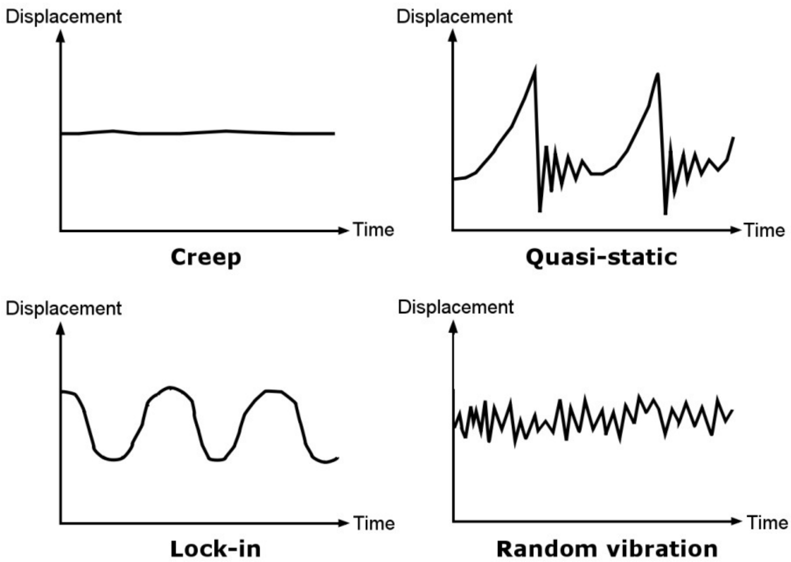

Figure 5: Schematic representation of typical ice-induced vibration modes.

OBSERVED VIBRATION MODES IN THE CURRENT TEST STUDY

The current test study successfully replicated quasi-static, lock-in and random vibration modes, as well as their transition modes. A similar scaling of the structure vibration modes with ice velocity was observed, with the tests configured in such a way that the transitions from mode to mode can be examined in details which would prove to be revealing.

The observed ice-induced vibration modes for the current test study can be refined into the following modes with the adopted terminologies:

Quasi-static: At low ice velocities, monotonic build-up of ice force deflects the structure in the ice direction (a loading phase), and a precipitate drop of ice force occurs when the ice in the vicinity in contact with the indentor fails, causing the structure to springs back in the opposite ice direction (an unloading phase), followed by a period of free structure vibration before the next interaction cycle begins. The structure displacement time history takes the form of a 'sawtooth' appearance. The relative velocity between the ice and the structure is low and the ice behaviour is believed to be ductile during loading phases. The ice failure behaviour is brittle during the high-rate spring-backs, characterized by crushing and extrusion of crushed ice.

Quasi-static-to-intermittent crushing transition: With increasing ice velocity, the average duration of the loading phases decreases, and the time between loading phases shortens and approaches the structure's first natural period. The structure displacement time history still maintains a general 'sawtooth' appearance without structure free vibration. An increase of ice crushing events was observed during loading phases.

Intermittent crushing: At intermediate ice velocities, the structure begins to vibrate in a harmonic manner as a result of the intermittent loading and extrusion (unloading) processes. The structure oscillates predominantly at its lowest natural frequency during this mode with highly-varying vibration amplitudes. Each vibration cycle can now be clearly separated into a loading phase and an unloading phase, with a notable absence of extrusion during loading phases.

Intermittent crushing-to-lock-in transition: With increasing ice velocity, the structure vibrates at its lowest natural frequency with increasingly uniform vibration amplitudes as well as with a higher average vibration amplitude.

Lock-in: At moderately high ice velocities, the structure vibrates at its lowest natural frequency with near uniform vibration amplitudes as well as with an even higher average vibration amplitude. The extreme regularity of the vibration amplitudes and scaling of the average structure velocity amplitude with ice velocity continue throughout the range of ice velocities during which lock-in occurs.

Lock-in-to-random vibration transition: With increasing ice velocity, the threshold for maintaining the lock-in vibration appears to have been reached – the average structure velocity amplitude ceases scaling with the ice velocity and variations between vibration amplitudes begin to grow.

Random vibration: At high ice velocities, the structure vibration ceases to be harmonic and the structure vibrates in a chaotic manner. Predominantly continuous brittle crushing with extrusion occurs throughout the entire interaction with no clearly distinguishable loading and unloading phases.

Examples of typical observed structure displacement time histories from the current test study are given in Figure 6, grouped according to the above terminologies.

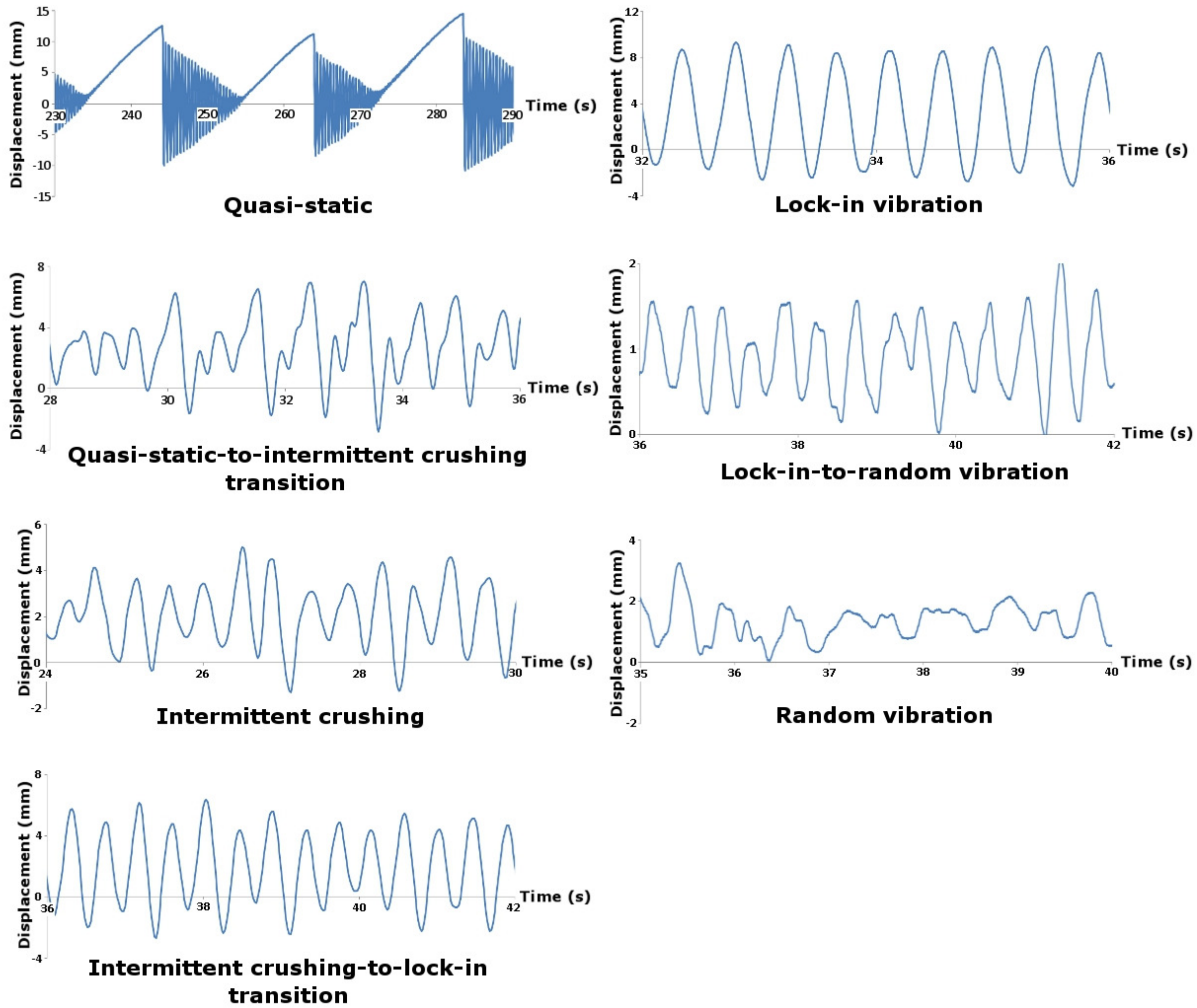

Figure 6. Displacement time histories obtained in the current test study.

MEASURES FOR DIFFERENTIATING ICE-INDUCED VIBRATION MODES

For the current test study, while identification of certain vibration modes, i.e. quasi-static, quasi-static-intermittent transition, and random vibration modes, can be straightforward due to their rather distinctive displacement time histories, identification of the other modes can be difficult without some sort of quantitative measure. With the results from the current test study, the qualities which can be used to differentiate the different vibration modes of harmonic nature are proposed herein to be the scaling of the average structure velocity amplitude with ice velocity, and the variability of the structure vibration amplitudes. The following sub-sections explain this approach.

Scaling of average structure velocity amplitude with ice velocity

Engelbrektson (1989; 1997) observed from measurements made at the lighthouse Norstromsgrund that lock-in vibrations occurred when the ice velocity was near the maximum velocity of the structure. Subsequently Karna et al. (2007) compiled a list of small-scale experiments and full-scale data in an attempt to verify this relationship during lock-in with the expression:

$$V_a = \beta\, U \tag{1}$$

where:

V_a	Average structure velocity amplitude
β	Ratio of average structure velocity amplitude to ice velocity
U	Ice velocity

Karna et al. (2007) noted that ratio β falls between 0.9 and 1.4 for the collection of data, and hypothesized that the structure and the ice must be in good contact (but not necessarily in complete contact throughout) during loading phases, and at the same time the ice must not fail during loading phases (otherwise there will be a precipitate drop in ice force). Therefore the structure must generally move at the same rate as the ice during lock-in and ratio β is expected to be close to unity.

It should be noted here that for a near sinusoidal structure velocity time history during lock-in, the structure velocity amplitudes approximately equal the maximum structure velocity (which was what Engelbrektson originally observed during lock-in vibrations of the lighthouse Norstromsgrund). For the purpose of the current test study, V_a is calculated as the mean of one half of the difference between the maximum structure velocity during the loading phase and the minimum structure velocity during the unloading phase in one vibration cycle $\left[V_a = \frac{\sum_i^n \{(v_{LP,i} - v_{UP,i})/2\}}{n}\right]$.

Variability of the displacement amplitudes

From the current test study results it has been known that a key differentiating feature for the harmonic modes is the variability of the displacement amplitudes. It is thus reasonable to expect the variability of the displacement amplitudes to change as the vibration mode changes from one mode to another. A parameter is created here, ratio γ, to represent this quantity. Ratio γ is the ratio of the standard deviation of structure vibration amplitude $D_{std\ dev}$ to the mean value of the structure displacement amplitude D_{mean}; ratio γ is otherwise known as the coefficient of variation in statistics. Another measure for variability could be based on velocity amplitudes instead of displacement amplitudes.

For the purpose of the current test study, the displacement amplitude of the i-th cycle is calculated as one half of the difference between the maximum structure displacement at the end of the i-th loading phase and the minimum displacement at the end of the i-th unloading phase $\left[D_i = \left(D_{LP,i} - D_{UP,i}\right)/2\right]$. D_{mean} and $D_{std\ dev}$ are then calculated as sample mean and sample standard deviation respectively for the entire displacement time history.

Quantitative definitions of ice-induced vibration modes

It is found that, using ratio β and ratio γ as defined above, a set of arbitrarily-defined rules can be created to differentiate the various observed vibration modes; this is given in Table 2. This set of rules with the chosen limits for the various modes paint a coherent picture tracing the mode-to-mode transitions for the current test study. At low ice velocities barely high enough to induce harmonic oscillation of the structure (at intermittent crushing mode), the structure vibrates with highly irregular displacement amplitudes, giving a high γ value and consequently a low β value. When the ice velocity is increased towards the lock-in velocity range, the β value of approximately unity quickly gets established, together with increasingly regular displacement amplitudes. Throughout the range of ice velocities in which lock-in occurs, scaling between the ice velocity and the average structure velocity amplitude is maintained with a β value of approximately unity. When the ice velocity is increased further, eventually the mechanism for maintaining this extreme regularity in motion during lock-in breaks down as the ice failure frequency gets increasingly high, and eventually reaches a stage where the displacement time history ceases to be harmonic.

Table 2. Adopted definitions of ice-induced vibration modes for the current test study.

Vibration Mode	**Ratio $\boldsymbol{\beta}$ $\left(=\frac{V_a}{U}\right)$**	**Ratio $\boldsymbol{\gamma}$ $\left(=\frac{D_{std\ dev}}{D_{mean}}\right)$**
Quasi-static	'Sawtooth' appearance	'Sawtooth' appearance
Quasi-static-to-intermittent crushing		
Intermittent crushing	$\beta < 0.9$	$\gamma \geq 0.4$
Intermittent crushing-to-lock-in transition	$0.9 \leq \beta \leq 1.1$	$0.2 < \gamma < 0.4$
Lock-in	$0.9 \leq \beta \leq 1.1$	$\gamma \leq 0.2$
Lock-in-to-random vibration transition	$\beta < 0.9$	$\gamma > 0.2$
Random vibration	Non-harmonic, chaotic	Non-harmonic, chaotic

DISCUSSION

Ratios β and γ

Table 2 is created solely for the purpose of differentiating the various observed ice-induced vibration modes in the current test study. For very rigid structures, it is expected that it would be difficult to maintain the extreme regularity of motion during lock-in, and that the velocity range between quasi-static and random vibration would be narrower. In addition, damping plays an important role in the context of vortex-induced vibration of structures. So it is expected that the structure's motion during lock-in would be suppressed for highly damped structures. For these reasons, while a similar trend may be reasonably expected to be applicable for other general structures, the limits for the various modes for any specific structure are most likely to be different than the limits given in Table 2.

In addition to providing some insight into the transition of ice-induced vibration modes with respect to ice velocity, the measures of β and γ provide a basis for comparing lock-in events of different structures under different ice conditions: How does one lock-in event compare to another lock-in event? Can all lock-in events be considered 'equal'? Without some basis comparisons can be difficult. Putting this into perspective, ISO 19906 (2010) states that lock-in "*can occur at intermediate ice speeds as the time-varying ice actions adapt to the frequency of the waterline displacements*", the vibrations are "*typically sinusoidal in this* *condition*", and "*the ice-structure interaction exhibits alternating phases of ductile loading and brittle unloading*".

Understanding the lock-in vibration

Experience with full-scale structures and small-scale experiments show that the relevant structure natural frequency is usually the lowest. Suppose that the relevant structure vibration frequency during lock-in is the lowest structure natural frequency *N*, and consider a simple scenario in which a semi-infinite ice floe with uniform thickness *h* is indenting a vibrating structure with a diameter *W* at a constant velocity *U*, nondimensional parameters in the form *U/NL*, where *L* denotes any parameter with the unit of length, may be formed. Palmer et al. (2010) examined two such parameters *U/Nh* and *U/NW*, and found encouraging results with *U/Nh*, supporting the conclusion that it is the relevant nondimensional parameter which controls the modes of ice-induced vibration. Yap (2011) studied the mechanics of lock-in vibration in a similar approach and proposed another nondimensional parameter, considering ice velocity, structure stiffness, structure's natural frequency, structure width, ice thickness and ice 'strength'[2], which is shown to be promising in describing the occurrence of lock-in. Subsequently Palmer and Bjerkas (2013) examined the role of synchronization and entrainment in the initiation of ice-induced vibration, using results from the Norstromsgrund and comparing them with a simple mechanical model.

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[2] The authors share the opinion that the notion of an ice 'strength' is flawed because when ice creeps it does not 'fail', and when brittle failure occurs there is no unique 'strength' since the failure stress is a function of many other factors. Nevertheless, the measure of ice compressive 'strength' is still commonly used and the uniaxial compressive 'strength' of different types of ice can be easily estimated using empirical formulas. Yap (2011) used uniaxial ice compressive 'strength' as an approximate to represent the peak nominal stress of ice during lock-in.

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