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Dynamic ice actions in the revision of ISO 19906

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ABSTRACT

The second edition of the ISO19906 design standard contains changes in the informative appendix concerning dynamic ice actions. Challenges in application of the previous approach and advances in understanding of the dynamic ice-structure interaction process were the main motivation for the revision. The new guideline provides relevant information for determining dynamic ice actions, but does not yet give a complete simplified design method. In this paper, the changes made in section A.8.2.6.1 covering dynamic ice actions on vertical and near vertical structures are discussed and remaining knowledge gaps are defined. Changes in the sections dealing with sloping structures and fatigue analysis were not made in the revision of ISO19906 and are therefore not considered. An important omission is identified related to the peak loads in intermittent crushing, which are potentially underestimated based on the new description. The main knowledge gap is found to be the definition of the ice drift speeds for which a specific mode of ice-induced vibrations may develop, e.g. intermittent crushing, frequency lock-in or continuous brittle crushing. These drift speeds depend on structural and ice properties. An estimation formula does not exist, hindering straightforward application of the ice load time traces as suggested in the standard.

KEY WORDS: Ice-induced vibrations; dynamic response; level ice crushing; frequency lock-in; intermittent crushing.

INTRODUCTION

Upon the release of the first edition of ISO 19906 (2010), questions arose as to the application of the defined method in Section A.8.2.6.1 which covers dynamic ice actions on vertical and near-vertical structures (e.g. Cammaert et al., 2011). These dynamic actions are often referred to as ice-induced vibrations and have shown to severely impact offshore structures in cold regions in the past (Bjork, 1981; Jefferies and Wright, 1988; Yue and Li, 2003).

In recent years, the approach for dynamic ice actions from ISO 19906 (2010) has been partially adopted by the wind industry and referred to in the governing IEC 61400 standard (2019). In the author's experience related to offshore wind projects, the application of the method is not straightforward and designers are often left with unanswered questions upon application.

Although the focus of ISO 19906 is on structures for oil and gas and therefore the application to other structures could be considered outside the scope of the standard, this does indicate that further development of design approach for dynamic ice actions is relevant.

The development of the 2nd edition of ISO 19906 (2018) re-opened the discussion around clause A.8.2.6.1, in which the author has been involved amongst many others. As a result, A.8.2.6.1 has been changed significantly, but a fully developed design approach has not yet been implemented.

In this paper, the update of Section A.8.2.6.1 is discussed with the main aim to identify gaps to which research in the coming years is to be focused to allow for an improvement of the design approach in the 3rd edition of the standard. Changes are discussed for the different sub-sections of A.8.2.6.1. Emphasis is placed on the definition of ice drift speeds associated with the different modes of dynamic interaction and the guidelines related to determining the structural response to continuous brittle crushing.

DISCUSSION OF THE UPDATE OF A.8.2.6.1

Section “A.8.2.6.1 Dynamic actions on vertical and near-vertical structures” in ISO 19906 (2018) is compared to the previous edition of the standard (ISO, 2010) indicating the main changes.

A.8.2.6.1.1 General

The revision of the general introduction now better reflects the importance of all three modes of interaction (intermittent crushing, frequency lock-in and continuous brittle crushing) in design. Background information has been moved from this section to A8.2.6.1.2.

Intermittent crushing is identified as the governing interaction mode for ultimate limit state analysis and also to contribute to fatigue. Frequency lock-in and continuous brittle crushing are furthermore important for fatigue analysis. The now suggested approach in design consists of two steps:

1. Determine the expected modes of interaction (i.e. intermittent crushing, frequency lock-in, and continuous brittle crushing) for the relevant ice conditions. Ice conditions here being combinations of ice thickness, strength, and drift speed which the structure may encounter during its lifetime;
2. Define the structural response based on one of three suggested approaches (A, B, C, below).

Step 1 remains an unresolved scientific challenge, limiting the development of a complete design approach, and is discussed further in a separate section of this paper. The fact that this point remains unresolved is also reflected in ISO 19906 as guidance is only given in the form of references to models which could be of use to the designer (Määttänen, 1987; Määttänen, 2008; Hendrikse et al., 2017).

The three approaches for determining the structural response are:

A. Based on ice action data from a similar structure in similar ice conditions;
B. Using prescribed force-time histories;
C. Using numerically-generated loading in a coupled model.

In practice, approach A is hardly ever applicable due to the strong non-linearity of the interaction problem which makes that the similarity requirements (“similar structure in similar ice conditions") are never met. Approach B is the basis for the remainder of the guidance in Section A.8.2.6.1, where pre-defined ice load time traces are given for each of the interaction modes. The downside of approach B is that the coupling between ice and structure is not included; however, the approach does allow for relatively simple and quick design calculations to be performed.

Approach C is the most complete as fully coupled simulations allow to capture the effect of different simultaneous sources of loading on the response of the structure and thus the ice-structure interaction. It also avoids the unresolved questions related to Step 1, as fully coupled models do not require the interaction mode to be pre-defined.

A note is made here that considering the coupling between ice and structure is generally not that important for structures considered for oil- and gas developments, which is the focus of ISO 19906, as these structures are generally relatively stiff under the ice loading they face. For offshore wind turbines the aerodynamic damping and coupled ice-structure-wind interaction leads to a significantly different impact of ice-induced vibrations when using a fully coupled simulation model such as that presented in Hendrikse and Nord (2019), compared to using approach B.

A.8.2.6.1.2 Time-varying interaction processes

This section of ISO 19906 (2018) provides background information on intermittent crushing, frequency lock-in, and continuous brittle crushing and has not been changed significantly.

A.8.2.6.1.3 Dynamic response to intermittent crushing

This section of ISO 19906 (2018) provides the prescribed force-time history which can be used to obtain the structural response to intermittent crushing. A saw-tooth ice load can be applied as shown in Figure 1. Three parameters need to be defined which are the peak load F_{max}, the saw-tooth period T which depends on ice drift speed, and the period of zero loading defined here as T_o.

Determination of F_{max} is done based on the static peak global ice action during continuous brittle crushing F_G (A.8.2.4.3, ISO, 2018). One important omission in the update which can have a significant impact on ULS design relates to determination of this peak ice action F_{max}. In the update, an important paragraph of A.8.2.4.3 has been removed which used to state that (ISO, 2010):

"*Data obtained both in the field and in laboratory show that brittle crushing, which prevails at ice speeds greater than 0,1 m/s, does not usually yield the highest actions. Maximum peak values occur when the ice speed is in the range of 0,003 m/s to 0,1 m/s. Further magnification in the apparent ice strength can arise at a low ice speed if the structure is compliant and an ice-structure interaction process known as intermittent crushing occurs.*"

Full-scale and model-scale observations indeed show that if intermittent crushing develops the peak load can be significantly larger than F_G (Finn et al., 1993; Kärnä et al., 2008, Kärnä and Muhonen, 1990), and it is suggested here to use a magnitude of twice F_G as also used in the design approach by Gravesen and Kärnä for sufficiently compliant structures (2009).

With respect to the failure period T it is defined that this is generally much longer than the lowest natural period and also that this is decreasing linearly with ice drift speed to become equal to the lowest natural period at which frequency lock-in develops for the structure at the smallest frequency lock-in related ice drift speed. This does not fully solve the question of what period to assume for a given ice drift speed, and what to assume for T_0, especially in the case where no frequency lock-in develops for the structure. A more explicit definition is still needed here, the challenge remains to define the ice drift speeds associated with intermittent crushing and the transition to frequency lock-in or continuous brittle crushing.

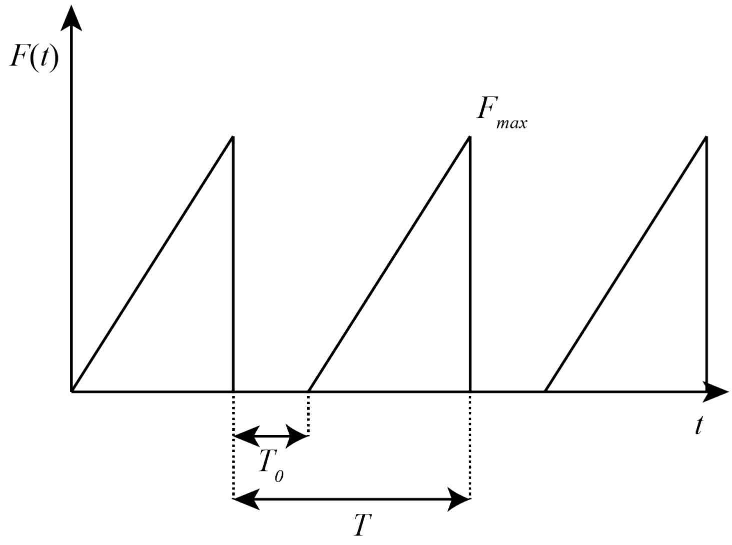

Figure 1. Example of a force time-history which can be used to obtain the structural response to intermittent crushing. The definition of T and T_0 as a function of ice drift speed remain to be quantified for the 3rd edition of ISO 19906. The maximum load F_{max} is suggested to be used as twice F_G (A.8.2.4.3, ISO, 2018) rather than F_G to account for the fact that intermittent crushing generally shows larger loads compared to peak loads during continuous brittle crushing.

A.8.2.6.1.4 Vulnerability to frequency lock-in

This section of ISO 19906 (2018) provides a check to determine which structural modes are likely to be susceptible to frequency lock-in. The section has been updated to include some description of the empirical parameter θ in Eq. A.8-85. Personal correspondence with the authors of the first edition of ISO 19906 (2010) has indicated that the derivation of this parameter is no longer available, but the consensus is that it includes effects of ice strength and structural width implicitly. Given that it was defined based on Cook Inlet measurements, it is considered mostly applicable to more slender structures. A re-derivation of this parameter in the future would be useful to allow quantification of the range of applicability of Eq. A.8-85.

What is not included is the definition of the most probable structural mode for frequency lock-in to develop in. Eq. A.8-95 often indicates multiple susceptible modes, but both model-scale and full-scale observations suggest that lock-in does not develop in multiple modes for defined ice conditions and a defined structure (Engelbrektson, 1983; Huang et al., 2007; Izumiyama et al., 1994; Toyama et al., 1983; Yue et al., 2001). This is identified as an open problem to be solved for the next update of the standard.

A.8.2.6.1.5 Dynamic response to frequency lock-in

The main change in this section of ISO 19906 (2018) relates to the removal of the suggested value of the maximum ice drift speed for which frequency lock-in can develop as $v_t = 0.06 f_n$ with f_n the natural frequency of the structural mode in which frequency lock-in develops (Eq. A.8-71, ISO, 2010). The reason for removal being that this relation was derived from a limited-in-scope full-scale dataset and was inconsistent with trends observed in, for example, the model-scale experiments by Huang et al. (2007).

The current approach provides the maximum ice drift speed for frequency lock-in in a given structural mode implicitly as the maximum structural velocity in the direction of ice motion divided by a factor 1.4 and obtained from application of the predefined time trace as shown in Figure 2 with q equal to 0.5. The minimum ice drift speed is obtained by taking q equal to 0.1. The thus obtained range of speeds associated with frequency lock-in has not been verified with data; nevertheless, it does give a better representation of the structural properties of influence, compared to the previous formula for v_t, on the range of ice drift speeds.

It is noted here that the use of the load time trace in Figure 2 to determine the fatigue contribution of frequency lock-in may result in an overestimation of the fatigue for structures where the mean response (i.e. mean stress) is important for fatigue as the mean ice load is overestimated by this approach.

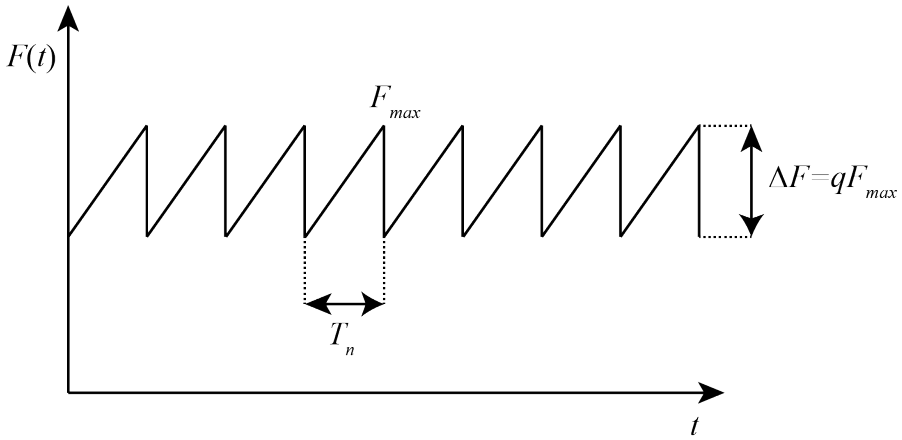

Figure 2. Force time-history which can be used to obtain the structural response to frequency lock-in. F_{max} is defined as F_G (A.8.2.4.3, ISO, 2018), q is defined to cover the range of 0.1 to 0.5. The period of the saw-tooth signal is taken as equal to the natural period of mode n in which frequency lock-in is expected to develop.

ICE DRIFT SPEEDS ASSOCIATED WITH THE MODES OF INTERACTION

The main remaining open question relates to the definition of ice drift speeds for which intermittent crushing, frequency lock-in, and continuous brittle crushing are expected to develop given a defined structure in defined ice conditions, which is defined as step 1 in the approach in ISO 19906 (2018) as explained above. If an estimation formula or method can be derived, which reflects the full-scale and model-scale observed dependencies on structural and ice properties, then that would allow for a clearer design methodology and improved guidelines to be developed. Attempts at development of formulas or estimation methods have been made in the past (Kärnä et al., 2007; Yap and Palmer, 2013; Ziemer and Hinse, 2017), but none has yet successfully captured all relevant aspects of the interaction. The limited data available for validation creates further difficulty in definition of an estimation method.

For now, a design solution based on the information presented in ISO 19906 (2018) is indicated in the flowchart in Figure 3. This approach is somewhat inverse, as it starts with checking for frequency lock-in based on A.8.2.6.1.4 and then assumes the other regimes to develop where frequency lock-in does not develop. This approach will still result in questions arising in design as the application of A.8.2.6.1.4 could result in no modes susceptible to frequency lock-in, which then makes it impossible to assign drift speeds to intermittent and continuous brittle crushing. It is, however, consistent with ISO 19906 (2018) and does not rely on other methods or models to pre-define the ice drift speeds associated with the different modes of interaction.

The use of coupled simulation models as defined as the third approach for determining the structural response in ISO 19906 (2018) is currently the only way to avoid having to deal with the assumptions underlying the flowchart in Figure 3.

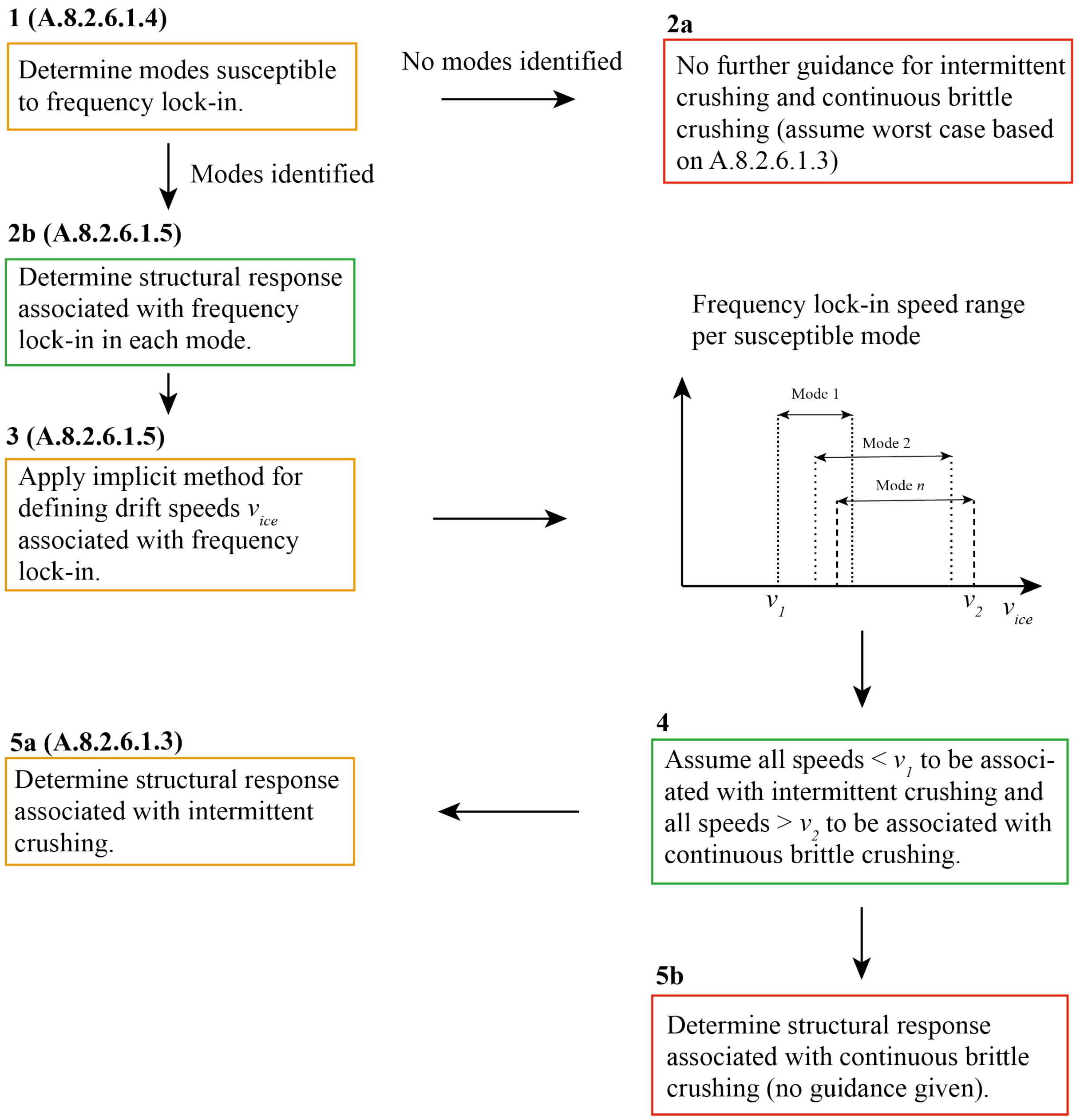

Figure 3. Dynamic analysis flowchart based on the 2nd edition of ISO 19906 (2018) Section A.8.2.6.1. Red color indicates steps which are not developed in the guideline. Orange color indicates steps which require further development, as described in the sections above. Green color indicates steps which are well developed and generally applicable in design.

STRUCTURAL RESPONSE TO CONTINUOUS BRITTLE CRUSHING

Guidelines for determining the structural response to continuous brittle crushing (step 5b in Figure 3) are not explicitly included in the 2nd edition of ISO 19906 (2018). Some information is given in Section A.8.2.6.1.2. The focus is naturally on the other two regimes as these would govern the ultimate limit state of the structure. Nevertheless, any structure in ice is likely to experience significantly more continuous brittle crushing events compared to intermittent crushing and frequency lock-in over its lifetime. Therefore, the contribution of continuous brittle crushing to fatigue of the structure might still be relevant to consider. Development of a spectral approach to be included in the next update, such as, for example, suggested by Kärnä et al. (2006), would close this gap.

CONCLUSION

The section on dynamic ice actions A.8.2.6.1 has been updated in the 2nd edition of ISO 19906, resolving some of the challenges associated with its application which were identified in the past years.

An important omission is identified related to the peak ice load during intermittent crushing, which can be a factor two larger than the in the revision defined peak load for relatively compliant structures.

What remains the biggest challenge in developing a simplified design approach to ice-induced vibrations is the definition of ice drift speeds associated with a certain mode of interaction (intermittent crushing, frequency lock-in, or continuous brittle crushing). For ultimate limit state design, this may not yield much of a problem in practice; however, if a large range of drift speeds associated with frequency lock-in and intermittent crushing has to be assumed for fatigue analysis, then this leads to severe overprediction of fatigue contributions.

The following points are identified for research which will aid the development of the 3rd edition of the standard:

- Development of an approach for definition of the ice drift speeds associated with the different modes of interaction given a specific structure in specific ice conditions;
- Revisiting the derivation of the parameter θ in Eq. A.8-85 to quantify the range of applicability of the equation;
- Definition of an approach to determine a single structural mode for which frequency lock-in is expected to develop;
- Definition of an approach for determining the structural response to continuous brittle crushing;
- Verification of correctness of the ice drift speed range associated with frequency lock-in now implicitly included in Section A.8.2.6.1.5.

The current guideline in Section A.8.2.6.1 can be used to make an estimate of the impact of ice-induced vibrations on the structure in the design phase. For a detailed analysis, the use of simulation models remains the only option to avoid having to deal with the in this paper described knowledge gaps in a design project.

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