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Interpretation and prediction of ice induced vibrations based on contact area variation

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ABSTRACT

Bottom founded offshore structures loaded by level ice can experience ice induced vibrations. The existing mathematical models of this phenomenon are, unfortunately, rather unreliable. The fundamental reason of this unreliability is the mechanism of the ice-induced vibrations which is not well understood and, consequently, does not seem to be properly accounted for in any of the existing models. In this paper a new mechanism is proposed which explains the majority of documented cases of ice induced vibrations. It is claimed that these are variations in the contact area between ice and structure that govern the global ice load, and thereby ice induced vibrations. A numerical model is developed incorporating the main aspects of the proposed mechanism. The numerical model captures general features of the interaction process. As shown by simulation of two experimental cases from literature, the model can predict all regimes of ice induced vibrations of compliant structures. Furthermore, the model reproduces the aperiodic character of ice loading on rigid structures.

1. Introduction

Level ice crushing against offshore structures can result in ice induced vibrations. First documented cases of such vibrations at the Cook Inlet, Alaska, date back to the late 1960's (Peyton, 1968; Blenkarn, 1970). Different regimes of ice action and ice–structure interaction can be distinguished. Classification of these regimes is commonly done based on indentation velocity and structural rigidity (Sodhi, 2001). The most important difference between rigid and compliant structures under ice loading is that for rigid structures the rate of ice deformation is governed exclusively by the ice sheet velocity, whereas for compliant structures it also depends on structural motion. For rigid structures three regimes of ice deformation and fracture are distinguished for increasing ice sheet velocities, namely the ductile regime, transitional regime, and brittle regime. For compliant structures the transitional and brittle regime are further subdivided into three distinct regimes of ice–structure interaction. Starting from the lowest ice sheet velocity these regimes are defined as: intermittent crushing, frequency lock-in, and continuous brittle crushing. The term 'ice induced vibrations' encompasses the latter three regimes. Frequency lock-in has received most attention over the years as it leads to the most severe vibrations of structures. Nevertheless, prediction of the occurrence of all three interaction regimes still remains a challenge.

Several theories exist for explanation of the occurrence of ice induced vibrations. Traditionally two main schools of thought can be distinguished. The first ascribes ice induced vibrations to occur as a result of a negative gradient in the dependence of ice strength on ice velocity (the so-called negative damping). The second defines a distinct fracture frequency in the ice, often referred to as spalling frequency (Gagnon, 2012), which when close to one of the natural frequencies of the structure results in resonance like behaviour. We discuss both these theories in short and define the main observations supporting and opposing them.

Sustained intermittent crushing and frequency lock-in can be explained to occur as a result of negative damping. As mentioned above, this negative damping is merely a result of the decrease of ice load with increasing ice velocity. For edge indentation by rigid structures such a dependence of the maximum global ice load on ice velocity has been reported (Singh et al., 1990; Takeuchi et al., 2001). As an explanation for this observation it is often stated that the strength of ice depends on the rate by which it is loaded referring to the observed negative gradient in the dependence of uniaxial compressive strength of ice on the loading rate in small-scale experiments (Michel and Toussaint, 1977). Models which rely on the dependence of ice strength on loading velocity (Blenkarn,

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1970; Määttänen, 1999; Huang and Liu, 2009; Kärnä et al., 1999) directly link the negative gradient in the global load to the negative gradient in compressive strength. It is questionable though whether this assumption is correct. A negative gradient in the dependence of the compressive strength of ice on velocity is not always identified in field observations on warm ice (Schwarz, 1970; Wu et al., 1974), whereas frequency lock-in and intermittent crushing are commonly observed during the spring months, when the ice can be considered as warm. From a modelling point of view, the velocity at which the negative gradient occurs has to be changed in order to obtain good predictions for structures with different degrees of compliance. This effectively results in ice behaviour dependent on structural properties. The latter unphysical consequence of the adopted assumptions limits the applicability of the models significantly, and, as a matter of fact, proves that the models do not capture the physics of the phenomenon correctly.

The second common approach is to assume a distinct brittle fracture frequency in the ice (Matlock et al., 1971; Sodhi, 1994; Gagnon 2012). Evidence for such a fracture frequency to exist is reported by Gagnon (1999). The occurrence of ice induced vibrations is either explained as a resonance condition between a periodic load and structure with a distinct natural frequency, or a classical synchronisation between two systems with distinct natural frequencies. The assumption of a distinct fracture frequency in the ice contradicts many observations of ice loads on rigid structures. As can be seen in the load signals obtained by Takeuchi et al. (2001), for example, the ice load in the brittle regime has no apparent periodicity. If a distinct fracture frequency in the ice would be the explanation for the occurrence of ice induced vibrations, it should be clearly visible from the load on a rigid structure. The distinct frequency reported by Gagnon (1999) could be argued to actually be a result of interaction with a compliant test system. The velocity of the structure during the tests is shown not to be constant, and typical of what would be expected during intermittent crushing on compliant structures. The measured frequency of ice fracture would in that case be a result of the interaction between ice and test system, rather than a pure ice property.

What can be concluded is that neither of the two above discussed approaches is complete in their predictions of ice loads for both rigid and compliant structures – something a physically correct model of ice should preferably be capable of. The developed models can mimic the dynamic ice–structure interaction, however their predictions often do not match experimental data (Jeong and Baddour, 2010; Muhonen, 1996).

In the opinion of the authors, the unreliability of the existing models stems from the fact that none of those actually incorporate the fundamental reason for either the decrease of the global ice load with increasing ice velocity or a quasi-periodicity of the ice loading in certain regimes of interaction. In this paper we propose a model that incorporates a mechanism that automatically reproduces the realistic part of the assumptions adopted in the existing models and provides an explanation of the majority of documented observations.

It is proposed that variations in the contact area between ice and structure govern the global ice load, and thereby ice induced vibrations. The increase of the contact area is ascribed to plastic deformations which occur when the ice velocity with respect to the structure is low. It is that increase in the contact area that results in the increase of the global load that assures the efficient energy transfer from ice to the structure and enables ice-induced vibrations.

The paper is structured as follows. Section 2 covers the introduction of experimental observations of the contact area variations during indentation with rigid structures, forced-vibration experiments, and ice induced vibrations. On the basis of these observations we define the underlying mechanism of contact area variation. In Sections 3 and 4 a numerical model is introduced which incorporates the proposed mechanism in a simplified manner. By application of the model to different interaction scenarios it is shown that the mechanism describes all main observations with respect to ice action on rigid structures and ice interaction with compliant structures presented in Section 2. A qualitative verification of the model in terms of its ability to reproduce the interaction regimes correctly is given in Section 5. A comparison of model predictions with two experimental cases is shown in Section 6.

2. Variations in the contact area during indentation

In this section we discuss experimental observations on variation of the contact area between ice and structure during indentation and its relation to the maximum global load. First we summarise observations on indentation of ice against rigid structures, which are structures which are both non-deformable and immovable in the context of this paper. Such structures do not interact with the ice and hence show 'pure' ice behaviour. Second, results from novel forced vibration experiments and a new set of free vibration experiments are introduced. The experimental campaign during which these experiments were performed is described in Määttänen et al. (2012). The section ends with a short summary of the proposed mechanism governing ice induced vibrations.

2.1. Variation of the contact area for indentation with rigid structures

Määttänen et al. (2011) and Takeuchi et al. (2001) used pressure sensors at the ice–structure interface during indentation tests with rigid structures. The measured local pressures provide an indication of the contact area between ice and structure in all three regimes of ice action on rigid structures. With respect to the contact area variation it is found that in the ductile regime ice pressure distributes over the full width of the indenter and thickness of the ice after a significant time of loading. Local pressures show little variation and the ice load increases gradually over time until ductile fracture occurs.

In the brittle regime a line-like contact area is formed close to the mid-section of the ice sheet (Joensuu and Riska, 1989). Local zones of high pressure are observed which change position along the width of the contact zone upon local fracture of the ice. The observed load and contact area in the brittle regime possess no apparent periodicity (Takeuchi et al., 2001).

It is of interest to discuss what happens in the transitional regime for rigid structures. The transitional regime being the range of velocities over which the deformation and fracture behaviour of the ice changes from predominantly ductile to predominantly brittle. Takeuchi et al. (2001) show that the average contact area between ice and structure is larger in the transitional regime, when compared to the brittle regime. This can be explained as a result of combined elastic and plastic deformation in this regime. The plastic deformation in the ice allows the contact area to increase by delaying local brittle fracture. Simultaneously with the increase in contact area, an increase in global load is observed. From these observations it can be concluded that the observed increase in global load at low velocities could be the result of an increase in loaded area.

2.2. Variation of the contact area during forced vibration experiments

In order to further illustrate the effect of the increase in contact area on the global load observed at the moment of local brittle fracture we discuss the results from forced vibration experiments per-