Cold Regions Science and Technology 121 (2016) 100–107

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

Edge indentation of ice with a displacement-controlled oscillating cylindrical structure

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ARTICLE INFO

Article history:
Received 30 March 2015
Received in revised form 26 September 2015
Accepted 27 October 2015
Available online 4 November 2015

Keywords:
Forced vibration
Ice–structure interaction
Contact pressure
Contact area
Frequency lock-in

ABSTRACT

Indentation tests were performed with a cylindrical structure subject to a controlled harmonic oscillation. The aim of the experiments is to study ice behaviour when loaded at a varying rate of indentation closely resembling that during frequency lock-in. Focus of the experiments is on the development of the global load, local pressure and contact area during indentation. To this end, a tactile sensor is installed at the ice–structure interface which allows for detailed measurement of these quantities. During the experiment the frequency and amplitude of structural oscillation were varied, as well as the indentation velocity. Results show that ice behaviour changes from brittle to transitional, and ultimately to ductile, as the relative velocity between ice and structure decreases during a cycle of oscillation. Both transitional and ductile behaviour result in an increase of the maximum global ice load upon fracture. The obtained increase in maximum global load depends on the duration of ductile behaviour of the ice. The longer the duration, the greater the increase in maximum global load compared to peak loads in the brittle regime. Tactile sensor measurements indicate that the increase in global load occurs as a result of a combined increase in contact area and mean contact pressure. The obtained results provide insight into the parameters influencing the occurrence of frequency lock-in of structures interacting with level ice.

1. Introduction

Ice induced vibrations can be experienced by compliant offshore structures interacting with level ice. Three regimes of ice induced vibrations are typically distinguished based on the characteristics of the time traces of the global ice load and structural displacement. These regimes are defined as intermittent crushing, frequency lock-in, and continuous brittle crushing (ISO19906, 2010). Intermittent crushing occurs at the lowest indentation velocities and is characterized by a saw-tooth pattern in the time traces of global load and structural displacement. Continuous brittle crushing occurs at high indentation velocities and is characterized by a quasi-random ice load pattern and small amplitude oscillatory response of the structure around an offset equilibrium position. For intermediate indentation velocities frequency lock-in may occur.

The frequency lock-in regime is characterized by sustained structural vibrations which are close to harmonic vibrations at a frequency slightly lower than one of the natural frequencies of the structure. These vibrations occur over a range of ice sheet velocities. The amplitude of structural vibration increases approximately proportionally to the increasing ice sheet velocity (Toyama et al., 1983). Examples of time traces of the structural displacement and ice load during frequency lock-in can be found in Izumiyama and Uto (1997), Kärnä et al. (1999), and Huang et al. (2007). Frequency lock-in has caused damage to jacket platforms and lighthouses in the past and, as a consequence, has been studied extensively (Yue and Li, 2003). As a result, several explanations for the occurrence of the vibrations exist, although a consensus on the governing mechanism has not been reached due to a lack of understanding of the complex physical processes of ice deformation and failure in this regime (Kärnä et al., 1999; Määttänen, 1999; Sodhi, 1994).

Local processes in the contact zone between ice and structure have been studied in the past by the application of tactile and pressure sensors (Määttänen et al., 2011; Sodhi, 2001; Takeuchi et al., 2001). Results for ice induced vibrations have been obtained in the regimes of intermittent crushing and continuous brittle crushing. Additionally, forces on non-moving rigid structures have been measured in the ductile and brittle regime. Measurements in the regime of frequency lock-in have not been widely reported. This is mainly due to the current level of understanding of the process which has not yet advanced enough to design experiments where frequency lock-in is guaranteed to occur. One must note though that the design used in the experiments by Huang et al. (2007), based on the original test setup by Timco et al. (1995), shows to be very susceptible to frequency lock-in. Unfortunately no local measurements in the contact zone were made during that experimental campaign.

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http://dx.doi.org/10.1016/j.coldregions.2015.10.013
0165-232X/

In this paper we approach the problem from a new angle by introducing a forced vibration setup as commonly applied in the field of fluid–structure interaction (Gopalkrishnan, 1993; Sarpkaya, 1978). This allows us to control the motion of the structure to be harmonic such that it closely resembles the motion of the structure during frequency lock-in. By application of a tactile sensor at the ice–structure interface the local pressure, contact between ice and structure, and global load can be studied. The first results of the tests, concerning the determination of added mass and added damping of ice, have been presented in Hendrikse et al. (2012). Here we present the main results which concern the local processes taking place in the ice during frequency lock-in. The results are deliberately presented in a concise manner, considering a single test wherever possible to illustrate the observations, but are applicable to all forced vibration tests performed in the experimental campaign.

The paper is structured as follows. Section 2 covers the introduction of the experimental setup and procedure. In Section 3 results of the experiment are presented with a focus on the development of global load, local pressure and contact between ice and structure. In Section 4 the results are employed to explain several observations in the case of frequency lock-in and define important parameters influencing the occurrence of such vibrations.

2. Experimental setup and procedure

In this section the experimental setup, procedure and method of data processing are introduced. The experiments were carried out in the Large Ice Tank at the Hamburg Ship Model Basin (HSVA) testing facility in August 2011 as part of the ‘Deciphering Ice Induced Vibrations’ (DIIV) test campaign. An overview of the experimental campaign as well as detailed technical drawings of the test setup can be found in Määttänen et al. (2012).

2.1. Experimental setup

The test setup, of which a schematic representation and picture are shown in Fig. 1, consists of a rigid beam with a cylindrical indenter with a diameter of 220 mm at the ice level. The beam is equipped with a Tekscan® tactile sensor #5513 at the ice level with a resolution of 3.5 Sensels/cm^2, a pressure range of 0–175 MPa and a sampling frequency of 100 Hz. The sensor is protected from direct ice abrasion by a 0.5 mm thick aluminium foil, and is made waterproof by application of silicone sealant. The tactile sensor is used to measure the global load, contact area and local pressure on the structure. The process of calibration of the sensor is described in detail by Metrikin (2011). About one third from the top of the structure the beam is rigidly connected to an EXLAR GSX50 electric linear actuator which controls the displacement of the structure. Displacements of the structure are measured with two lasers at a sampling frequency of 100 Hz.

All experiments were performed on a single day within a single columnar grained ice sheet which was produced in NaCl-doped water with a salinity of 6.8‰ by means of seeding. During the growth process the air temperature in the ice tank was −22 °C. The crystal size of the ice was controlled by scraping the ice from underneath. Air bubbles with 200–500 μm diameter were embedded in the growing ice sheet to ensure the brittle behaviour of the ice as described by Evers and Jochmann (1993). Subsequent to the ice growth process the temperature was raised in order to hit the target ice thickness of 60 mm and target ice properties. During the experiments the temperature of the ice was approximately −2 °C. After the experiments samples of the ice sheet were collected from the sides and middle of the ice sheet at intervals of 10 m along its length for determination of relevant ice sheet properties. Tests on these samples showed an average ice density of 830 kg/m^3, average salinity of 3.3‰, and average uniaxial compressive strength of 270 kPa at a strain rate of 10^{-3} s^{-1}. At the locations where the samples were taken flexural strength tests were also performed which showed an average flexural strength of 150 kPa.

2.2. Experimental procedure and test matrix

The indentation distance of the structure into the ice during a single test is defined as the result of a constant indentation velocity v_{ice}, which is controlled by the main carriage in the ice basin, the controlled

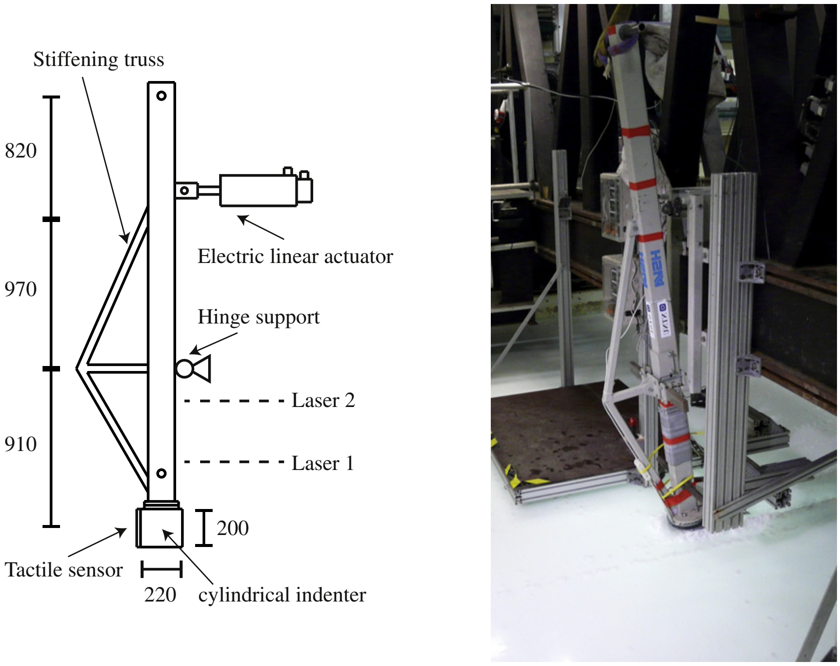

Fig. 1. Test setup used in forced vibration experiments. The setup consists of a vertical rigid beam with a cylindrical indenter at the ice level. An electric linear actuator is installed in order to control the motion of the structure. Displacements are measured by two lasers and the contact area, local pressures, and global load are measured by a tactile sensor. All measures are in mm.