Cold Regions Science and Technology 119 (2015) 1–15

Contents lists available at ScienceDirect

Cold Regions Science and Technology

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

Laboratory experiments to study ice-induced vibrations of scaled model structures during their interaction with level ice at different ice velocities

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ARTICLE INFO

Article history:
Received 12 November 2014
Received in revised form 14 May 2015
Accepted 29 June 2015
Available online 4 July 2015

Keywords:
Ice-induced vibrations
Model-scale testing
Force and response characteristics
Contact-zone characteristics
Ice crushing

ABSTRACT

A simplified model of a typical bottom-founded structure was forced through ice sheets in a laboratory experiment to study ice-induced vibrations. The ice forces exerted on the structure are identified in conjunction with the response of the entire structure using a joint input-state estimation algorithm. Novel insights into ice-induced vibration phenomena are obtained by comparing, on different time scales, measured and estimated response quantities and forces/pressures. First, the identified forces, ice velocities and time-frequency maps of the measured responses are presented for a series of ice-induced vibration tests. It is shown that the ice forces excite more than one mode of the structure and that the transition ice velocity at which the vibrations shift from the first to the second mode increases with reduced foundation stiffness and reduced superstructure mass. Second, a detailed analysis of the interaction between the structure and the ice edge is performed on a smaller time scale by comparing the locally measured pressures at the ice-structure interface to the identified structural responses and forces. It is shown that structural vibrations at a frequency higher than the dominant vibration frequency cause cyclic loading of the ice edge during intermittent crushing. These vibrations led to an increasing loading rate prior to ice failure. During an event that shows the tendencies of frequency lock-in vibrations, the structural response was dominated by a single vibration frequency.

1. Introduction

Ice crushing on bottom-founded structures may induce severe vibrations, potentially threatening operational reliability and structural integrity. Over the past 50 years, considerable effort has been spent on investigating the phenomenon of ice-induced vibrations. The physics remains, however, not yet fully understood.

The characteristics of the ice crushing forces differ depending on the structural compliance and velocity of the ice (Sodhi and Haehnel, 2003). As ice-induced vibrations are determined by the crushing failure, different laboratory studies have been performed to explain the crushing failure in relation to ice-induced vibrations; see e.g., Määttänen (Määttänen, 1979; Määttänen et al., 2012), Kärnä (Kärnä, 1995; Kärnä et al., 2003a, 2003b), Toyama et al. (1983), Sodhi (2001), Gravesen et al. (2005), Barker et al. (2005) and Huang et al. (2007).

At low ice velocities and with the interaction governed by intermittent crushing, the dominant vibration frequency was found to be proportional to the structural stiffness (Browne et al., 2013; Määttänen, 1975; Nakazawa and Sodhi, 1990). At higher velocities, the dominant vibration frequency tends towards one of the natural frequencies, and lock-in vibrations may occur. Single degree of freedom (SDOF)-oscillators have dominated the research in laboratory experiments in recent decades. In principle, ice forces may excite all modes of a structure depending on the location of the ice-action point and the frequency content of the ice forces. Määttänen measured a great contribution of the second mode both in full scale (Määttänen, 1975) and laboratory experiments (Määttänen, 1983), revealing that it is inadequate to consider only the first mode. A limited number of studies have subsequently been published on bottom-founded multi degree of freedom (MDOF) laboratory structures; see e.g. Kärnä et al. (2003a).

The discovery of the line-like contact (Joensuu and Riska, 1988) brought a new dimension to the fundamentals of ice crushing and drew more attention towards the ice–structure interface. When the ice failed by brittle flaking against a transparent plate, they saw a narrow band of contact spots across the indenter width, the "line-like" contact. During experiments on a flexible structure, Sodhi (2001)

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http://dx.doi.org/10.1016/j.coldregions.2015.06.017
0165-232X/

showed that the local pressures grew simultaneously during the load build-up at low indentation speeds. At the onset of ice failure, the indentation speed increased by two orders of magnitude, and the pressure changed progressively during the ice failure. Recent small-scale indentation experiments by Wells et al. (2011), Taylor et al. (2013) and Browne et al. (2013) also link the ice force and failure characteristics to the pressure. The latter associated failures of high pressure zones to measured cyclic force patterns up to a frequency as high as 250 Hz. For a literature review on crushing failure and the ice behavior adjacent to the indenter, see Jordaan (2001), Sodhi (2001), Sodhi et al. (1998) and Wells et al. (2011).

In this contribution, we use a novel approach to elucidate the influence of the structural state on ice-induced vibrations. Using a set of response measurements, linear filtering theory is applied to estimate the interaction. Both the states and the forces are treated as unknowns and jointly estimated using a finite element model and a joint input-state estimation algorithm (Gillijns and De Moor, 2007). This algorithm has been modified (Lourens et al., 2012) for application to reduced-order models, where the modification enabled force and state estimation also when the number of forces and/or response measurements exceeded the number of structural modes used to construct the model. The algorithm requires no prior assumptions on the dynamic evolution of the forces, allows for uncertainty in the model equations as well as the measurements, and requires only a limited number of response measurements. The estimated states and forces are optimal in the sense that they are linear minimum-variance unbiased estimates. Recently Nord et al. (2015) applied the original algorithm (Gillijns and De Moor, 2007) to ice-induced vibrations. They demonstrated that the force and response estimates were of acceptable accuracy when information about the first natural frequency was accessible. The computational effort is significantly reduced with the reduced-order models, allowing real-time estimation of the forces and states, a great advantage for monitoring also full-scale arctic structures. While Nord et al. (2015) demonstrated that the framework was applicable to ice force identification, this paper further utilizes the advantage of simultaneous force and response identification to explain how the structural motion affects the ice pressure at the indenter.

In what follows, the identified forces, velocities, and time-frequency maps of the responses of the Deciphering Ice-Induced Vibrations (DIIV) test campaign are presented first. Secondly, the interaction during two different ice-induced vibration regimes is studied in detail by means of the jointly estimated response and ice force in combination with the measured local pressures acting on a cylindrical indenter. When these data are presented together, they provide novel insights into the influence of the modal contributions on the ice–structure interface.

2. Dual force and state estimation

2.1. System equations

The force is treated as an unknown concentrated load acting on a linear time-invariant structure that is represented by a finite element model consisting of a limited number of structural modes:

$$\ddot{\mathbf{z}}(t) + \mathbf{\Gamma}\,\dot{\mathbf{z}}(t) + \mathbf{\Omega}^2\mathbf{z}(t) = \mathbf{\Phi}^{\mathrm{T}}\mathbf{S}_p\mathbf{p}(t) \tag{1}$$

where $\mathbf{z}(t) \in \mathbb{R}^{n_m}$ is the vector of modal coordinates and n_m the number of modes used to assemble the model. The excitation vector $\mathbf{p}(t) \in \mathbb{R}^{n_p}$ is specified to act on the desired locations through the force influence matrix $\mathbf{S}_p \in \mathbb{R}^{n_{DOF} \times n_p}$, where n_p is the number of force time histories and n_{DOF} is the number of degrees of freedom. $\mathbf{\Gamma} \in \mathbb{R}^{n_m \times n_m}$ is the diagonal damping matrix populated on the diagonal with the terms $2\xi_j\omega_j$ where ω_j and ξ_j are the natural frequency in rad s^{-1} and damping ratio corresponding to mode j, respectively. $\mathbf{\Omega} \in \mathbb{R}^{n_m \times n_m}$ is a diagonal matrix containing the natural frequencies ω_j and $\mathbf{\Phi} \in \mathbb{R}^{n_{DOF} \times n_m}$ is a matrix collecting the mass-normalized mode shapes.

2.2. State-space model

The continuous-time state vector $\mathbf{x}(t) \in \mathbb{R}^{n_s}$, $n_s = 2n_m$ is defined as follows:

$$\mathbf{x}(t) = \begin{pmatrix} \mathbf{z}(t) \\ \dot{\mathbf{z}}(t) \end{pmatrix} \tag{2}$$

whereby the equation of motion of second order in Eq. (1) can be organized as a first-order continuous-time state equation

$$\dot{\mathbf{x}}(t) = \mathbf{A}_c\mathbf{x}(t) + \mathbf{B}_c\mathbf{p}(t) \tag{3}$$

where the system matrices $\mathbf{A}_c \in \mathbb{R}^{n_s \times n_s}$ and $\mathbf{B}_c \in \mathbb{R}^{n_s \times n_p}$ are defined as

$$\mathbf{A}_c = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ -\mathbf{\Omega}^2 & -\mathbf{\Gamma} \end{bmatrix}, \mathbf{B}_c = \begin{bmatrix} \mathbf{0} \\ \mathbf{\Phi}^{\mathrm{T}}\mathbf{S}_p \end{bmatrix}. \tag{4}$$

The measurements are arranged in a data vector $\mathbf{d}(t) \in \mathbb{R}^{n_d}$, in which the observations can be a linear combination of displacement, velocity and acceleration, with n_d the number of data measurements. The data vector is constructed as follows:

$$\mathbf{d}(t) = \mathbf{S}_a\mathbf{\Phi}\ddot{\mathbf{z}}(t) + \mathbf{S}_v\mathbf{\Phi}\;\dot{\mathbf{z}}(t) + \mathbf{S}_d\mathbf{\Phi}\;\mathbf{z}(t) \tag{5}$$

where the selection matrices $\mathbf{S}_a$, $\mathbf{S}_v$ and $\mathbf{S}_d \in \mathbb{R}^{n_d \times n_{DOF}}$ are populated according to the spatial location at which acceleration, velocity, displacement and/or strain are measured. Eq. (5) can be transformed into state-space form using Eqs. (1) and (2):

$$\mathbf{d}(t) = \mathbf{G}_c\mathbf{x}(t) + \mathbf{J}_c\mathbf{p}(t) \tag{6}$$

where the matrices $\mathbf{G}_c \in \mathbb{R}^{n_d \times n_s}$ and $\mathbf{J}_c \in \mathbb{R}^{n_d \times n_p}$ represent the output influence matrix and direct transmission matrix, respectively, defined as follows:

$$\begin{aligned} \mathbf{G}_c &= \left[\mathbf{S}_d\mathbf{\Phi} - \mathbf{S}_a\mathbf{\Phi}\mathbf{\Omega}^2 \quad \mathbf{S}_v\mathbf{\Phi} - \mathbf{S}_a\mathbf{\Phi}\mathbf{\Gamma}\right] \\ \mathbf{J}_c &= \left[\mathbf{S}_a\mathbf{\Phi}\mathbf{\Phi}^{\mathrm{T}}\mathbf{S}_p\right]. \end{aligned} \tag{7}$$

In discrete time under a zero-order hold assumption and given a sampling rate of $1/\Delta t$, Eqs. (3) and (6) become:

$$\mathbf{x}_{k+1} = \mathbf{A}\mathbf{x}_k + \mathbf{B}\mathbf{p}_k \tag{8}$$

$$\mathbf{d}_k = \mathbf{G}\mathbf{x}_k + \mathbf{J}\mathbf{p}_k \tag{9}$$

where

$$\mathbf{x}_k = \mathbf{x}(k\Delta t),\ \mathbf{d}_k = \mathbf{d}(k\Delta t),\ \mathbf{p}_k = \mathbf{p}(k\Delta t),\ k = 1, \ldots, N$$

and

$$\mathbf{A} = e^{\mathbf{A}_c\Delta t},\ \mathbf{B} = [\mathbf{A} - \mathbf{I}]\mathbf{A}_c^{-1}\mathbf{B}_c$$

$$\mathbf{G}_c = \mathbf{G},\ \mathbf{J}_c = \mathbf{J}.$$

2.3. Joint input-state (JIS) estimation algorithm

Assuming that the system matrices are known, the joint input-state estimation algorithm can be used to jointly estimate the forces and states from a limited number of response measurements. By introducing the random variables $\mathbf{w}_k$ and $\mathbf{v}_k$, which represent the stochastic system and measurement noise, respectively, the discrete-time state-space equations become the following:

$$\mathbf{x}_{k+1} = \mathbf{A}\mathbf{x}_k + \mathbf{B}\mathbf{p}_k + \mathbf{w}_k \tag{10}$$

$$\mathbf{d}_k = \mathbf{G}\mathbf{x}_k + \mathbf{J}\mathbf{p}_k + \mathbf{v}_k \tag{11}$$