DYNAMIC ICE STRUCTURE INTERACTION

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Contents

Summary

Dynamic ice structure interaction can develop while moving level ice is breaking in crushing mode against a fixed offshore structure. The structure responds to varying loads with its natural modes of vibrations. The effect of ice load becomes amplified when the dynamic ice load increases the structural response and at the same time the dynamic motion of the structure makes the ice failure easier. Together these factors contribute to the energy interchange from the driving ice load to structural kinetic and strain energy. As the energy input into the structure is most efficient at a natural mode frequency, one of the lowest structural modes can start to dominate the ice failure frequency and paves way into the state of frequency lock-in vibrations. This is a severe -resonant type -loading case and can easily cause damage to an offshore structure. Dynamic ice structure interaction raised the interest of ice researchers and engineers after the first Cook Inlet oil production platforms exhibited unexpected dynamic response in 1960's. Thereafter similar cases have been experienced in almost all ice-infested waters where fixed offshore structures have been prone fore the action of moving level ice. In some cases even severe structural damages have been encountered. The scientific research to understand the physics of ice structure dynamic interaction has been going on now already over 40 years. By studying the ice mechanical properties, especially ice strength dependence on loading rate and ice disintegration mechanics, performing both scale-model and full-scale testing, and developing numerical simulation methods, a holistic view of the ice-structure dynamic interaction is evolving that allows to design structures immune to adverse dynamic ice structure dynamic interaction effects.

1. Introduction

1.1. Description

Solid ice sheets at large bodies of water in nature can often drift and move while driven by winds and currents. Solid ice hitting a stationary offshore structure will generate heavy loads. While a constant thickness level ice is moving at constant velocity and crushing against an offshore structure, one would intuitively expect almost a constant ice load -with only some random variations. In engineering practice, a normal method is then to design the structural capacity to exceed the maximum ice load with a certain factor of safety. Structural failures due to ice action have disproved this kind of thinking. The reason is the unexpected violent ice and structure dynamic interaction.

Under ice action the structure deflects and stores both elastic and kinetic energy until ice fails. Then, as structure starts to spring back against the ice movement, the relative velocity between ice and structure increases, ice failure occurs easier, and a part of the elastic energy in the structure is transforming into kinetic energy. If during the next ice edge pushing against the structure both the ice load and kinetic energy are acting together the displacement amplitude of structure is further increasing. Then more energy is accumulating into the structure during each ice failure cycle and vibration amplitudes are increasing. The process is self-excited and has a natural limit. After the structural velocity response at the waterline exceeds ice velocity, the contact between ice and structure is lost. Then further energy accumulation into the structure reaches its limit because the internal structural damping energy losses would increase continuously with increasing vibration amplitudes. In such a limit state of vibrations the net energy inflow during each vibration cycle is zero while all the energy input from ice pushing is dissipated into ice crushing and structural damping.

The origin of ice induced structural vibrations has been under dispute for over 40 years.

Explanations for the phenomenon have included:

- ice has a tendency to break at certain frequency
- ice has a tendency to break at certain failure length
- ice/structure dynamic interaction is a self excited vibration process

The first two of these explanations have been proven wrong in scale model tests simply by changing the mass or stiffness at the model superstructure. This has changed the frequency or the apparent failure length provided ice velocity in the same ice field has been kept constant. The present understanding is that dynamic ice structure interaction initiates from dynamic instability and is a nonlinear self-excited process.

In the nature more familiar physically comparable dynamic interactions are:

- disk break screeching
- chalk squealing on blackboard
- violin sound
- milling machine chatter

Common in these three cases is a mechanical system capable to store both elastic and kinetic energy, and an interaction process -friction -that depends on the relative velocity between the constant driving velocity and the response velocity of the mechanical structure. This dependence is analogous to ice crushing strength dependence on loading rate, resulting from the difference of ice velocity and the response velocity of the structure in the direction of ice movement. In milling machines both the friction and material strength dependencies on relative velocity are present during chattering.

Physically different but analogical dynamic interactions where structure captures energy from the environment are:

- flow velocity induced vortex shedding in piles
- flutter of aircraft structures at constant airspeed

In vortex shedding the vortex separation is dependent on the pile diameter and on water flow velocity. Each vortex separation induces lateral load pulse in addition to drag load. Lateral load pulses store elastic and kinetic energy to the pile. At certain velocity the vortex separation rate hits that of the lateral vibration frequency of the pile. During the flutter of aircraft structures elastic deformations -bending and twisting -interact with structural inertia and aerodynamic loads.

With increasing velocity the rate of these changes will get close to those corresponding to natural mode frequencies and allow energy storing into the structure and cause violent vibrations. All these can be explained and modeled by the self-excited vibration theory. Similar physical and mechanical properties play role in the dynamic ice-structure interaction.

1.2. History

No reports have been found on the occurrence of moving ice induced vibrations before the incidents at the Cook Inlet, Alaska, at the beginning of 1960's. It is likely that already well before this there have been ice-induced vibrations in bridge piers and on piers in marinas. However, due to low economic impact, or no threat to environment, no research results have been published. The bridge pier vibrations were studied in 1970's and later, after the Cook Inlet incidents in Canada and USA, Montgomery, Neill, Haynes. First reported structural failures occurred in the fall 1973 at the Gulf of Bothnia in Finland as soon as moving ice thickened over 10 cm and induced severe resonant type vibrations in new steel lighthouses. In 1980's and 90's oil/gas production structures experienced disturbing continuous vibrations at Bohai Sea while tidal currents moved ice fields. All these incidents occurred in relatively slender and flexible bottom founded structures. Then in 1986 the blunt and massive caisson retained island Molikpaq in the Beaufort Sea experienced severe periodically repeating ice loadings under the action of thick multi-year ice that threatened the structure's foundation stability due to increasing pore pressure in the foundation soil (Jeffries et al, 1988).

1.3. Dynamic Ice-Structure Interaction Definition

The dynamic ice structure interaction means that both the ice and the structure interact through the contact process, and that the action of each party changes the dynamic state of the other. Quite evident is the driving energy of ice storing into the kinetic and elastic energy of the structure. More hidden is the effect of the dynamic response of the structure to change the ice failure process against the structure, especially the rate dependent ice crushing failure mode from ductile to brittle and vice versa. The energy storing into the structure is the key issue causing much higher stresses in the structures compared to otherwise similar but static ice-structure interaction cases.

The effect of strain rate from ductile to brittle ice failure can be coupled to micromechanical phenomena during ice-structure interaction. Initially, as structure is moving close to ice velocity, the creep deformation is taking place. The increasing structural resistance increases stresses in the ice and local micromechanical changes - damage -is starting to occur and the load is gradually transmitted mostly through the localized high pressure ice contact (Joensuu, 1988; Jordaan et al 2008; Gagnon, 2011). At last, the failures of these high-pressure zones initiate brittle crushing after which a new contact is established with initial ductile load build up for the next loading cycle.

The rate dependence of ice crushing failure can dominate the ice failure synchronizing into the natural frequency of the structure and yield to the most severe loading case: the frequency lock-in. During frequency lock-in the ice failure repeats close to the natural frequency of the structure. This state can prevail at a relatively large ice velocity range. The frequency lock-in can also shift from one natural frequency of the structure to another if ice movement velocity changes sufficiently. If a natural frequency of the structure starts to control the ice failure frequency it brings with the local ice failure synchronization in wide structures and at different legs of a multi-legged structure.

1.4. Adverse Effects on Structures

Even small dynamic loads -especially if close to a natural frequency -will cause annoying structural vibrations, can increase maximum stresses in the structure, and require the structural components to be designed against fatigue. Dynamic ice structure interaction in wide and multi-legged structures can synchronize the otherwise unrelated local ice failures at interaction zones to occur simultaneously which further increases significantly the overall load level from that of uncorrelated loads.

Foundations carry through the ice loads to the foundation soil but the underlying soil resistance to loads is dependent on the frequency content of loads. In many soil types the ambient pore pressure controls the maximum load capacity. Soil dynamic deformation due to ice structure interaction will increase pore pressure and reduce soil strength. This was what happened to Molikpaq in April 1986 during a multi-year ice floe action (Jeffries et al, 1988). The dynamic fluctuating ice load action increased the foundation pore pressure to such a level that a serious threat was close for the whole structure to start move along with the ice. Luckily the ice movement stopped before any significant damage occurred.

2. Full-Scale Observations and Measurements

2.1. Cook Inlet

Cook Inlet is over 270 km long and in average about 20 km wide fjord at the Gulf of Alaska, 60°N, with the city of Anchorage at the North-Eastern end. The area is strongly affected by tidal currents up to 2 m/s with up to 9 m tidal range. The sea ice can be present from November to May and its thickness can grow up to 1 m. Due to tidal actions the ice cover is not uniform but mostly broken and rafted. With continuously and strongly varying ice parameters -especially ice thickness and velocity -it is quite likely that any offshore structure will encounter dynamic ice loads. In addition to ice actions, the Cook Inlet platforms are also prone for earthquake actions.

The first Cook Inlet oil and gas production structures after 1964 were the first to raise research interest on resonant type of vibrations during dynamic ice-structure interaction. Between 1964 -68 a total of 14 offshore structures were completed and they included a monopod, and three-to four-legged platforms, Fig, 1 and 2. Peyton, 1966 and 1968, studied thoroughly Cook Inlet ice strength and measured ice loads against offshore structures as well as structural response in dynamic ice structure interaction. He measured ice crushing strength dependence on strain rate and noticed significant ice strength reduction at increasing load rate, Figure 3. Interestingly, similar ice strength vs. loading rate dependence was later measured also at Bohai Sea, Figure 4. Peyton measured the ice load against a vertical pile that was fixed in front of the platform. He observed solid ice to crush into small pieces while compressing against the pile, breaking a path about the width of the pile, highest loads at slow ice velocities and with increasing ice velocity dynamic ratcheting type ice load fluctuations. At higher ice velocities the load peaks reduced to about half from the maximums. He described: “The failing ice can cause resonant vibration in structures, and the forces are large enough to resonantly vibrate structure weighing several thousand tons”. However, in his studies of dynamic loads his conclusion was “The ice force oscillation is an ice property and is not primarily a function of the response of the structure”.

Figure 1. Monopod “Trading Bay”

Figure 2. Four-legged platform "Bruce"

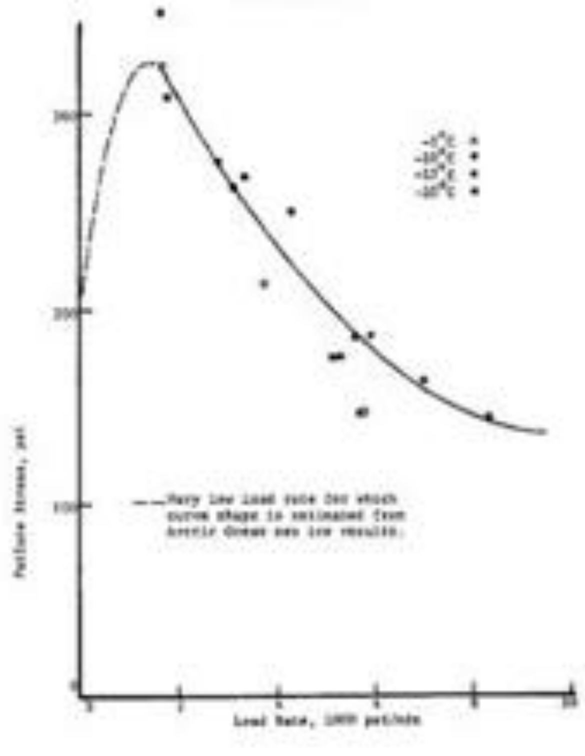

Figure 3. Cook Inlet ice strength (Peyton, 1966) (1 psi ≈ 7 kPa)

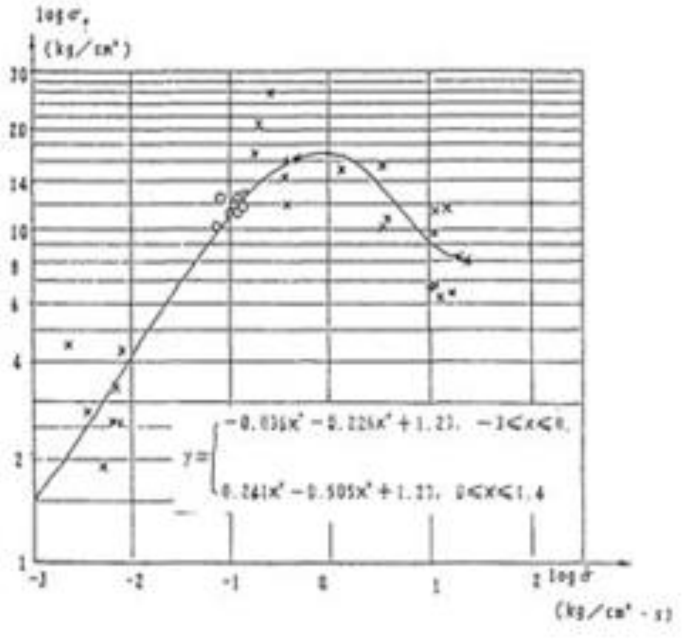

Figure 4. Bohai Sea ice compressive strength (Meng &Wang, 1987) (kg/cm^2 ≈ 0.1 MPa)

At the end of the 1960's Blenkarn studied also dynamic ice structure interaction at Cook Inlet structures. He coupled the ice and the structure together through the interaction load, and took into account the vibration velocity of the structure. Then the loading rate of the ice will be dependent on the sum of constant ice velocity and the vibration velocity of the structure. Hence the ice structure interaction load becomes dependent also on the dynamic response of the structure. Based on Peyton's ice strength dependence on the loading rate Blenkarn (1970) presented a single degree of freedom dynamic equation of motion. The condition for dynamic instability gave means to calculate at what conditions ice induced vibrations can arise. Physically this condition means that the momentary energy input from the ice failure exceeds the amount of energy dissipation in the structure. Physically this means that for the inspected single degree of freedom system the ice induced negative damping -the interpretation of the decreasing ice load with increasing interaction velocity -is equal to that of structural damping. This was the first model to suggest how to design structures immune to ice induced resonant vibrations.

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Biographical Sketch

Mauri Määttänen, Emeritus professor, Aalto University, neé Helsinki University of Technology (HUT), Espoo, Finland, MSc in aeronautical engineering, HUT 1968 and Doctor of Technology (PhD, HUT) 1978. Researcher in Laboratory of Strength of Materials (Mechanics of Solids), HUT 68-70, Associate Professor in Mechanics of Solids, University of Oulu 1970-77, Professor of Technical Mechanics, University of Oulu 1978-87. Professor of Mechanics of Solids, HUT 1988-2006, retired Nov. 2006. Invited Professor in Arctic Technology, Norwegian University of Science and Technology (NTNU) 100-year anniversary grant by Det Norske Veritas, Trondheim 2011-2012. Presently 25 % of time Researcher in Arctic Technology in NTNU, Norway. Main research interest field is Ice Mechanics, especially dynamic ice-structure interaction, and ice loads. Interest to ice research started in 1972 during the in-field studies of flexural strength of brackish water ice. A year later the new Finnish steel lighthouses in the Gulf of Bothnia experienced severe vibrations and structural damage due to moving ice. The then initiated dynamic ice-structure interaction research work under his supervision together with the University of Oulu and Finnish Board of Navigation eliminated the problem by introducing vibration isolated lighthouses and vibration isolation for the delicate components in the superstructures of other aids-to-navigation structures. Sabbatical at US Army Cold Regions Research and Engineering Laboratory in 1978-80 allowed to carry through the first scale model tests for better understanding the "mysterious" dynamic ice structure interaction. Based on his patent he has designed 12 steel lighthouses with vibration isolation to the Finnish fairways. He has participated Confederate bridge pier cones ice load design and has evaluated the ice load design of St Petersburg flood protection barrier structures. He has been the Finnish country member both in POAC and IAHR Symposium on Ice organizations, Chairman of IAHR working group on Ice Forces on Structures 1979-84, chairman Working Group of IALA

(International Association of Lighthouse Authorities) to develop design guidelines for Ice Effects on Lighthouses 1980-85, and the President of IAHR Section on Ice Research and Engineering 1992-96. He was the Finnish country member in the ISO TC67 SC7 WG8 Ice load code development 2002 – 2010

(ISO 19906 was published 2010). His hobbies include cross country skiing, flying (commercial pilot) and scuba diving.