DECIPHERING ICE INDUCED VIBRATIONS - DIIV

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ABSTRACT

While moving level ice is crushing against a fixed offshore structure it can evoke severe vibrations, especially if repeating ice crushing events synchronize with a natural frequency of the structure. First the problem was encountered in Cook Inlet, Alaska in 1960's and then ten years later in the Gulf of Bothnia, Finland. Scientific research has been conducted now for 50 years to explain the physical and mechanical background of ice induced frequency lock-in vibrations but still no unanimous understanding exists. Major reasons are due to inadequate data - both in scale model tests and especially in full-scale measurements. To cover pitfalls in scale model tests the Norwegian University of Science and Technology (NTNU) initiated at the beginning of 2011 the DIIV project - Deciphering Ice Induced Vibrations. The planned scale-model tests were accepted as a project in the EU-HYDRALAB IV Transnational Access Program. This paper describes the design of the test set-up, instrumentation and calibration, conducted tests, and the present status of data analysis and planned future work.

1. BACKGROUND

Intuitively one could assume that ice load would be constant while a level ice sheet is moving at constant velocity and crushing against an offshore structure. However, ice crushing is a random process with variable areas of solid ice edge in contact and subsequently shattering against the surface of the structure. As the structure is not completely solid its deformations will have an effect on ice edge load build up and failure. Especially if the deformation occurs along the total ice edge contact area at the natural frequency of the structure the total ice load can start to vary also at - or close to - this frequency. This can lead to the frequency lock-in - a resonant type state of ice load variations. This state is a nonlinear process depending on ice strength dependence on loading rate, ice disintegration, and broken pieces clearing mechanisms that are all coupled by the contact with the structure and to the structures state of displacement and velocity. As a whole this is a nonlinear dynamic ice structure interaction process.

After the first in-field encounters of severe dynamic ice-structure interaction events, engineers and scientist started to make research on the origin of the phenomenon. The first proposal based on Cook Inlet measurement data was that ice has a tendency to fail at a rate of 1 Hz, (Peyton 1968). As this was also close to the natural frequency of the structure in question another model - self-excitation - was proposed, (Blenkarn 1970). The Gulf of Bothnia steel lighthouse vibration problems gave further support to this latter proposal since vibrations occurred at both the first and second natural frequencies of the lighthouse (Määttänen 1975). Later many more scientists promoted and argued on these rather differing explanations.

The basic reason for differing views was the missing holistic understanding of the whole dynamic ice-structure interaction process due to inadequate full-scale data and pitfalls in scale-model tests laboratory data. The direct full-scale ice action measurement against an offshore structure is still an unrealized challenge. The general dynamic response of the structure can be
easily measured but the missing link is how to get into details what happens in the ice structure contact zone both spatially and with time. In full scale it is also impossible to get the detailed ice data: ice crystal structure, temperature and salinity that have a strong effect on ice strength and its disintegration process. All these are needed to understand and develop a theoretical or numerical model to explain the ice structure interaction.

Scale model test reduces the number of unknowns: ice properties can be measured more accurately, the structure can be simpler and instrumentation more comprehensive. The main advantage is that the properties of ice and structure can be varied easier to find out the effect of a single parameter. Uncertainties arise from scaling down both the ice and structure properties. Literature study indicated that the major pitfall in previous scale model tests has been in reducing the model structure into only a single degree of freedom oscillator. Real offshore structures have numerous natural modes that each contribute to the real ice-structure interaction, especially into interaction rate dependent ice crushing behaviour.

The Norwegian University of Science and Technology (NTNU) initiated the Sustainable Arctic Marine and Coastal Technology project (SAMCoT) in 2011. Dynamic ice-structure interaction was evaluated as one of the key topics for a more thorough research. A scale model test proposal was prepared for Hydralab IV and accepted to be carried through in HSVA test basin in Hamburg, Germany. The actual tests were conducted in August 2011. This paper describes the model structure design, test program, data analysis this far, and further planned data utilization.

2. TEST SET-UP

The main objectives of the scale model structure were to present a real multi-degree of freedom structure at about 1:10 scale ratio, to provide at least two distinct natural modes, an easy way to vary both the natural frequencies and mode shapes, and waterline structure diameter, Määttänen et.al. 2012. Cauchy scaling laws were used both for the ice and the structure instead of normal ship model test practice of Froude scaling because gravity loads are not relevant in dynamic ice structure interaction.

Figure 1. a) Test structure installed on the carriage. b) Typical natural mode shapes.
The test structure for dynamic ice-structure interaction free vibration tests was a vertical elastic beam attached by vertical support beams and spring elements to the HSVA carriage bridge main box beam, actual picture Fig. 1a and the sketch in 2a. The typical distinct natural modes are plotted in Fig. 1b. The natural frequencies and mode shapes can be easily adjusted by varying the horizontal spacing of vertical connection beams and by the changing tuning masses. The diameter of the ice crushing cylinder could as well be changed, three different diameters were used, 100, 220 and 400 mm. Each time the pile settings were changed a dynamic calibration with a measured step relaxation load was executed before testing in order to determine frequency response functions from this known dynamic ice load to the strain, displacement and acceleration measuring transducers in the test pile.

**Figure 2.** a) Test structure free vibration set-up  
           b) Forced movement set-up

During the forced movement tests the test pile was modified into a stiff configuration by adding a reinforcing frame, Fig 2b. As all the tuning masses were also removed the pile behaved as a rigid beam. The upper spring element was removed and an electrically driven actuator piston was attached to the pile upper support point. The actuator provided sinusoidal movement that was mirrored at opposite phase on the cylinder to crush the moving ice with a sinusoidal varying velocity which was superposed on the constant ice movement velocity. Then it was possible to solve the ice crushing load components due to the added damping and added mass loads. These are in 90 and 180 degrees phase shift with the movement, Hendrikse et.al. 2012.

The instrumentation was designed to measure dynamic ice load, ice crushing cylinder displacement and velocity from the measured data, Määttänen et. al. 2012. For the ice load the indirect method based on frequency response function was chosen. Dynamic strain, displacement and acceleration response was measured at different locations of the test pile. The dependence on the true ice load can be solved by making dynamic calibration with a known - measured - step relaxation calibration load at the location and direction of the real ice load. Then the frequency response function can be calculated and used to solve the true ice load histories by utilizing Fourier transforms from the measured response signals. Whenever the test structure mechanical properties were changed the dynamic calibration had to be done for each different configuration.
For the first time a tactile sensor was installed on the cylindrical test structure crushing the ice to directly measure the interaction pressure distribution at different phases of an ice-structure dynamic interaction cycle. The objectives were to find out both the vertical and circumferential pressure distributions, and crushing pressure synchronization. The sensor was protected from direct ice abrasion by a 0.5 mm thick aluminium foil, and it was waterproofed by silicon. Fig. 3 gives an example of recorded narrow line like contact during crushing at 180° sector with colour code in kPa. The total height or tactile sensor is 156 mm.

![Figure 3. Contact line during crushing.](image)

### 3 TEST PROGRAM

The measurement program included a test matrix with varying ice mechanical properties, ice thickness, ice velocity, structure waterline diameter, surface roughness, structure compliance, natural frequencies and modes, and as a fresh approach - an analogy to vortex shedding testing - a forced sinusoidal ice crusher movement superposed to the constant ice velocity. A total of six ice fields were frozen in HSVA tank and used for 58 different test sets during the two weeks from 16.8 to 1.9.2011. The four first ice fields were used for free vibration tests and the last two for the forced sinusoidal movement tests.

Dynamic ice structure interaction is a capricious phenomenon. The onset of frequency lock-in vibrations depends on many parameters that have to match. In advance it is hard to decide at what parameter settings: ice thickness and strength, ice velocity, structural stiffness and mass distribution - natural modes and frequencies - the conditions for FLI can be met. The ice velocity is the most important parameter. In the first tests the velocity was increased from 20 to 300 mm/s at constant acceleration 2 mm/s². Constant acceleration testing gives a pseudo static velocity for a long enough time period for the FLI to develop. Immediately after a test the visual inspection of response data indicated at which velocity range the dynamic response was highest. Then the remaining part of the ice field could be used for a more detailed rerun at that velocity range only. The four first ice fields were used for searching a parameter combination for distinct FLI. However, even though the whole available parameter space was checked no strong and long lasting FLI appeared - only short duration weak occurrences lasting few seconds. Both first and second mode FLI incidents were recorded. As the ice-velocity increased, the response frequency shifted between the structural modes (Nord et al. (2013)). Also a shift from a possible sub-harmonic frequency to the second mode occurred in test #2200 while a 41 mm thick level ice was moving at about 100 mm/s and accelerating at a constant rate of 2 mm/s, Test #2200 Fig. 4.
Two ice sheets were devoted for the forced sinusoidal movement tests. Ice thickness and pile diameter were kept constant while both the constant ice velocity and sinusoidal movement amplitudes were varied in different tests. However, some data sets with large sine amplitudes had to be rejected due to inadequate actuator control - the actuator control unit could not brake enough and its zero position slipped. This caused an offset movement to original zero point and distorted the large amplitude purely sinusoidal motion.

4. DATA ANALYSIS

Preliminary data analysis, in situ visual inspection of dynamic response amplitudes, immediately after test runs was used to provide guidance how the test parameters should be chosen for the next test runs. The data indicated that with steadily increasing ice velocity intermittent ice crushing failures started to repeat at closer intervals and could stay for short duration close to natural frequency periods. In some tests even a large jump from one frequency to the second occurred, Fig. 4. The jump phenomenon from one natural mode to another is earlier observed in a full-scale offshore structure in the Gulf of Bothnia at constant ice velocity due to the change of ice thickness. Waterfall type plots demonstrated better how the ice crushing frequency approached natural frequencies, Fig. 5. The preliminary data indicated a promise of FLI but not for long time periods, not even in constant velocity tests at most promising ice velocity.

Figure 4. Dynamic response shift from a sub-harmonic of the 1st to 2nd natural mode.

Figure 5. Dynamic response intensity with increasing ice velocity.
The data analysis already at this stage has indicated the importance of higher natural modes participation into energy interchange during dynamic ice structure interaction and promoting the state of FLI. Interaction ice load energy flow with time or for each vibration cycle,

\[ E(t) = \int_0^t F(x)dx \]

indicates how much energy from ice is fed into the structure. If this remains constant then the same energy is dissipated into ice crushing and various damping effects - friction between ice and structure, energy needed to push crushed ice into water and above ice surface, hydrodynamic losses, and structural damping. Results indicate definite difference depending whether one or more natural modes are observed. This suggests that single degree of freedom dynamic ice structure dynamic interaction testing is questionable.

The more thorough data analysis continued after tests both in NTNU and in TU-Delft. NTNU utilized frequency response function to solve true dynamic ice load histories, ice load velocity dependence, and dynamic response possible coupling with natural frequencies, Nord et.al. 2012 and 2013. The forced sinusoidal movement testing proved the existence of negative damping and mass concepts, Hendrikse 2012.

5. **PLANNED ACTIVITIES**

The Hydralab/DIIV forced movement further data analysis on added mass and added damping effects in dynamic ice structure interaction is refined and be included into PhD thesis by MSc H. Hendrikse next year. Presently more advanced frequency response function analysis methods are adopted into the DIIV data analysis. As the ice velocity was varying during ice sheet constant acceleration testing the Kalman filter approach has been adopted. Preliminary results, Nord et.al. 2014, look promising and after refinement will be included into his PhD-thesis. The Hydralab/DIIV measurement results offer a well documented database for testing the numerical models in the recently initiated campaigns to improve the accuracy of numerical models to understand and predict the capricious dynamic ice structure interaction phenomena.

6. **ACHIEVEMENTS**

Altogether six model ice fields with thicknesses between 40 to 90 mm were tested at ice velocities from 0 to 350 mm/s. The structural configuration was changed to give natural frequencies from 7.5 to 30 Hz. This was accomplished by changing both the tuning masses and support stiffness of the test pile. Also the ice crushing cylinder diameter was varied: 100, 220 and 400 mm. The cylinder surface roughness was also changed in order to verify friction effects. Various velocity dependent dynamic ice load histories were measured at different structural configurations.

All the three in literature defined ice-structure dynamic interaction scenarios were captured: intermittent, frequency lock-in and random. The most wanted - frequency lock-in vibration - sustained only for short times, e.g. 10 to 15 vibration cycles.

The test structure behaved mostly according to design expectations. The change of a structural configuration was straightforward and could be changed in a short time in between tests.

Only one pitfall was the servo-controlled actuator in forced sinusoidal movement tests. As the movement direction changed the servo control, that was giving signal to push against the ice, should have changed instantaneously to pull in the direction of constant ice movement while maintaining the unaltered pushing load Hence some of the controlled movement data has
uncontrolled slippage in position. The model ice properties that are normally tuned for ship model tests - with ice failure in bending - required colder testing environment in order to maintain sufficient crushing strength. Data points harvesting was started to establish the correlation of ice crushing strength dependence on routine test basin bending and uniaxial compression measurements data.

The data analysis indicates energy interchange between the first and higher natural modes of the structure to be important in promoting dynamic ice structure interaction. This suggests that scale model tests with a single degree of freedom models are inadequate to predict the dynamic behaviour of a real full size multi-degree of freedom structure under ice loads.

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REFERENCES


Peyton, H.R., 1968. Ice and Marine Structures, Parts 1, 2 and 3. Ocean Industry