LABORATORY TESTS OF ICE INDUCED STRUCTURE VIBRATIONS

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ABSTRACT
Laboratory tests were performed to simulate the dynamic interaction of cylinder, slender structure and moving ice sheet. Specific laboratory preparation procedures and parameters design that are fundamental to the physical mechanism of interaction are described. Ice induced self-excited vibrations were observed in tests and frequency lock-in phenomenon was achieved. Simulation in the laboratory of full-scale ice-structure interactions reveals good agreement with field data and theoretical mechanisms validating self-excitation theory.

KEYWORDS: Ice; Ice induced vibration; Ice-Structure interaction; Laboratory test; Modeling test.

INTRODUCTION
The phenomenon of ice-induced vibrations have been investigated for nearly four decades but the physical process of dynamic ice force formation is still not well understood. The dynamic interaction between a moving ice sheet and a cylinder slender structure during crushing mode has been of particular interest.

There are two explanations to characterize the excitation force of ice in crushing failure. Most researchers believe that the vibration is forced (Michel, 1978, Neill, 1976). The second explanation describes ice-induced vibrations as a form of self-excited vibration (Määttänen, 1977). As we know that self-excited vibration occurs when the force is controlled by the oscillation of the structure. As lack of convincing data and physical process explanation, there are some debates on the existence of ice-induced self-excited vibration.

Recent years, the comprehensive full scale tests were conducted on several offshore jacket structures (Yue, 2005). That disclosed that during ice interacts with vertical structure in crushing failure with the ice speed changing from slow to fast there exist three ice force models which induce quasi-static, steady-state and random vibrations. It is also concluded that the steady state vibration and random vibration correspond to the self-excited and forced vibration respectively (Yue, 2002). In order to confirm the field tests results a small scale test system, which considers the dynamic behavior of the model structure, is established.

This paper outlines the design process of experimental parameters, and the results of data analysis provides significant insight in understanding the mechanisms of this particular ice-structure interaction.
FIELD TESTS RESULTS

The objective of this paper is to describe the laboratory setting and results, a brief discussion of the theory of 3 modes of ice-induced vibrations, however, is necessary before depicting the experiment. Ice speed plays a fundamental role in ice-induced vibrations. The relative velocity between ice and structure is a crucial element that determines the vibration mode of interaction.

Quasi-Static Vibration: At low ice speed of less than approximately 20mm/s in-situ, the relative velocity between ice and structure is low. As the structure moves in the same direction as the ice load, the loading rate to ice is low and ice undergoes plastic deformation and in the ductile damage zone. When the ice load has reached its limit value, a long ice sheet will break to fragments, the structure will vibrate freely with damping (Figure.2).

Steady-State Vibration: In the special velocity range of 20-40mm/s in-situ, ice may cause steady-state vibrations where the amplitude remains nearly changeless for long time.

Forced vibration theory is not valid in this phenomenon, because if characteristic break length of ice and characteristic frequency of ice load really exist, the break length must remain a constant for so long time, it’s impossible for sea ice, a material whose properties are quite random. In other words, frequency of ice load must be locked by the oscillation of structure (Figure.3, the smooth curve is displacement of structure whereas the toothing one is ice load), so ice-induced steady-state vibration is self-excited.

A physical mechanism is given to explain this vibration: During this mode the loading rate of ice may enter ductile-brittle transition zone, at first half of one period, structure moves in the same direction of ice motion, a lot of micro-crack forms in ice, energy dissipation of micro-crack is little, most energy of motion from ice sheet is stored as deformation energy of structure, after reaching maximum deformation, structure spring back, micro-crack connect and break, redundant deformation energy is released.

Random Vibration: When ice speed is fast, loading rate of the ice is high and ice undergoes brittle failure, the breaking period and amplitude of vibration is random (Figure.4).
LABORATORY TEST SETUP

Laboratory tests modeling the interaction between moving ice sheet and a cylinder, slender structure have been conducted several times over the years. The loading method, ice thickness, ice velocity, driving system, pile diameter, and so on have changed in each successive experiment. Määttänen (1978), Kärnä, Turunen (1989) and Muhonen et al. (1992) have all conducted laboratory tests using designed parameters attempting to validate proposed theories. The experimental setup delineated below is specific for modeling the dynamic ice-structure interaction. Parameters have been chosen to best simulate properties of steady-state vibration, and consequently validate self-excitation theory.

Loading System

Currently, there are two methods of modeling ice loading: active loading and passive loading. In active loading, the model structure is built on the basin floor and the ice sheet is grown in a unidirectional sliding carriage. During experimentation, the ice sheet is pushed past the structure. Active loading physically resembles ice loading in the field. In passive loading, the ice is grown in an ice tank. The structure is mounted through load cells to a sliding carriage and pushed through the ice sheet.

In dynamic testing of slender structures, passive loading should not be used. During passive loading, the moving structure is supported by a rigid frame. The structure response will not be the response of the structure, but in fact, the response of the entire carriage system with inaccurate frequencies and properties such as stiffness and mass. In active loading, the structure is bottom-bounded, consistent with the prototype system. The response of the structure is not affected by supporting masses or rigid attachments.

A single-degree of freedom model structure was built in a refrigeration room 5.5 m long and 3.3 m wide with a height of 4.7 m. The model structure was built to the floor and can carry a 3-ton load. A sketch of the system is shown in Figure.5. The pile is placed at the top of the model structure (Figure.6). Parameters of the structure are defined in a subsequent section. A photograph of the ice carriage inside the refrigerator room is shown in Figure.7.

Figure.5 Sketch of Experiment Apparatus
Figure.6 Simple Idealization of Ice-Structure Interaction
Driving Machine

The driving machine is powered by hydraulic pressure, whose maximum pushing force is about 500kN. This force produces the steady motion of the ice carriage during loading. The position of the hydraulic actuator is shown in Figure.8. The stroke of the driving machine is approximately 1000 mm. During testing, the displacement meter $D_3$ was set up between the support frame and the ice gutter to measure ice velocity.

Scaling Laws

According to scaling law theory, only when all the scaling equations are satisfied will the model system reflect the real behavior of the prototype system. However, not all scaling equations are consistent. When some equations are satisfied, the others will be unsatisfied. During the design process, it is necessary to make the model system abide by the dominant scaling equations which are most significant to the experimental objective. The other unessential equations should be softened. Scaling laws (Määttänen, 1979, 1980, 1983) typifies the test of modeling ice-structure interaction, which is also simple to apply.

Two scale factors, $\lambda$ and $\lambda_s$, were used to scale the model system from the prototype system. The geometrical constant $\lambda = 10$ was used to scale the dimensions of the model system to 1/10 of prototype system. The material constant $\lambda_s = 1$ was used to scale the properties of ice, which means that properties of model ice should be the same as prototype ice properties. The following scaling terms were derived:

- Length dimensions: $L_p = \lambda L_m$
- Ice strength: $\sigma_p = \lambda_s \sigma_m$
- Stiffness of the structure: $K_p = \lambda K_m$
- Top mass of the structure: $M_p = \lambda^3 M_m$
- Ice force: $F_p = \lambda^3 \lambda_s F_m$
- Damp Coefficient: $C_p = \lambda^2 C_m$

where the subscript p and m signify the prototype system and the model system, respectively. According to the scaling law, the specific parameters shown in Table.1 were derived.
### Table 1: Parameters Design

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Ice Thickness (m)</th>
<th>Pile Diameter (m)</th>
<th>Stiffness (N/m)</th>
<th>Mass (tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prototype</td>
<td>0.4</td>
<td>1.2</td>
<td>$\approx 10^7$</td>
<td>$\approx 3000$</td>
</tr>
<tr>
<td>Model</td>
<td>0.04</td>
<td>0.12</td>
<td>$\approx 10^6$</td>
<td>3</td>
</tr>
</tbody>
</table>

### Model Ice Preparation

Preparing model ice for experimental use first originated in the mid 1950s at the Arctic and Antarctic Scientific Research Institute in Leningrad, U.S.S.R. (Shvayshtyen, 1957). The process is both challenging and meticulous. In ice modeling tests, the properties of ice are very important. Temperature, salinity, and crystal structure all influence the properties of ice. Therefore, the strength, elastic modulus and other properties of ice need to be properly adjusted. Model ice can easily be altered by adding a specific dopant to the model ice mixture.

Model ice that contains both fresh water and salt water closely models sea ice in the Bohai Sea. The Yellow, Luanhe, Haihe, Liaohe, and Dalinhe rivers empty $8 - 9 \times 10^{10} \text{ m}^3$ of fresh water per year, increasing sea ice characteristics to that of freshwater ice, so fresh water adjustments must be made. Table 2 contains the ratio of salt water to fresh water used in each experiment.

### Table 2: Salt Water to Fresh Water Ratio for producing model ice

<table>
<thead>
<tr>
<th>Experiment Number</th>
<th>(#1) 07/01/05</th>
<th>(#2) 27/01/05</th>
<th>(#3) 11/04/05</th>
<th>(#4) 25/04/05</th>
<th>(#5) 29/06/05</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salt Water: Fresh Water</td>
<td>100% : 0</td>
<td>0 : 100%</td>
<td>50% : 50%</td>
<td>50% : 50%</td>
<td>75% : 25%</td>
</tr>
</tbody>
</table>

According to the scaling law of geometry, the aspect ratio of pile diameter to ice thickness $D/h$ should be the same as the real platform. Thickness of real sea ice causing ice-induced self-excitation is about $300 - 350 \text{ mm}$. Therefore, the ice thickness used should be controlled under $50 \text{ mm}$. The experiment was run with a uniform ice thickness of $45 \text{ mm}$ approximately.

### Measurement Apparatus

Two accelerometers were placed on the sides of the model structure. Two displacement meters were set up between the supporting frame and the model structure. A third displacement meter was placed between the ice gutter and the supporting frame, graphing the data from this displacement meter over time yields the ice velocity.

In order to measure ice load accurately, strain gauges were attached on both sides of the pile. Before formal testing, the relationship between strain and ice force was calibrated. A stiff beam was fixed in the front of ice gutter and the driving velocity was set to a low value. Force data was obtained through the pressure sensor, strain data was obtained through the strain gauge, and the relationship between the readings was obtained. A diagram of the measurement apparatus is shown in Figure 9.
The total number of recorded channels was 7. They are listed in Table 3. Both accelerometers placed on opposite sides of the model structure produced similar signals. All signals were recorded in real time. The sampling rate was 50 Hz. A video camera was set up approximately a meter above the ice-pile interaction to observe the crushing process.

### Table 3 Measured Signals

<table>
<thead>
<tr>
<th>Channel</th>
<th>Signal</th>
<th>Abbreviation</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Acceleration</td>
<td>A1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Acceleration</td>
<td>A2</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Displacement</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Displacement</td>
<td>D2</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Displacement</td>
<td>D3</td>
<td>Ice Velocity</td>
</tr>
<tr>
<td>6</td>
<td>Strain Gauges</td>
<td>F1</td>
<td>Ice force</td>
</tr>
<tr>
<td>7</td>
<td>Strain Gauges</td>
<td>F2</td>
<td>Ice force</td>
</tr>
</tbody>
</table>

**EXPERIMENT DATA**

During conducted 5 tests only ice velocity was changed in each test process. Other parameters such as ice thickness, stiffness and mass of model structure were all held constant in order to be consistent with the scaling law. The recorded acceleration, displacement and ice load was analyzed.

Our expected self excited vibration was not achieved in the beginning four tests, but in the last test, ice velocity was 40.9 mm/s. Figure 10a shows the ice load over time. Spectral analysis shows that the dominant frequency was 3.9 Hz (Figure 10b). Figure 10c shows the displacement detail. Figure 10d is the PSD of displacement. It had a dominant frequency of 3.9 Hz also.
By comparing the spectral density graphs of displacement and ice load, it is apparent that they both have dominant frequency at 3.9 Hz, which shows the characteristics of self excited vibration and frequency lock-in phenomenon.

CONCLUSION

Analysis shows that self-excitation is the correct theory in characterizing ice-induced steady-state vibrations. The presence of lock-in phenomenon on three different structures is significant in proving the existence of self-excited vibrations. Confirming field data in the laboratory has proven to be extremely useful. The process of ice-modeling tests is fundamental in obtaining proper data and making sure that the model system accurately reflects the prototype system. Making sure parameters adhere to the scaling laws and that ice is prepared properly are important factors in modeling dynamic ice-structure interactions. Proving self-excitation theory, however, leads only to further more complicated issues such as mathematically modeling the ice load and understanding micro-crack behavior in relation to self-excited vibrations. Laboratory tests will indeed be profitable to help understand further theories concerning ice-induced self-excited vibrations. At this point, great progress has been made in characterizing this complex interaction.
REFERENCES


