An attempt has recently been made to identify the added mass and added damping of level ice in interaction with a vibrating structure. To this end forced vibration experiments were carried out in the ice tank at the Hamburg Ship Model Basin (HSVA) testing facility in Hamburg in August 2011. The test setup consisted of a rigidly mounted cylinder which, connected to an actuator, could be forced to oscillate with different frequencies and amplitudes. The ice indentation velocity was varied between 0.01 m/s and 0.1 m/s during the experiments, where the ice was made such as to fail mainly in crushing. The setup was equipped with strain gauges and laser sensors in order to measure the ice forces and the model displacement respectively. At the ice-structure interface a tactile sensor was installed in order to facilitate simultaneous measurement of the ice pressure on the structure. Added mass and added damping parameters have been identified for several cases from the measured force and displacement signals. The presence of negative damping, as is also found from indentation tests with stationary towed cylinders, is reconfirmed in this experiment. Additionally it is found that for low indentation velocities also the added mass can become negative. This new result provides a new angle of approach for the development of predictive models for dynamic ice-structure interaction.
1. Introduction

Dynamic interaction between a moving ice sheet and a structure can, under certain conditions, lead to severe structural vibrations. These vibrations have been observed to occur for different kinds of structures, slender and wide, and are known for their potential to cause severe damage. The phenomenon has been studied for years and various phenomenological predictive models have been under development in the past decades (Matlock et al., 1969; Määttänen, 1978; Kärnä et al., 1989; Sodhi, 1994; Hendrikse et al., 2011). However, the physical processes taking place in the course of the dynamic ice-structure interaction are still not well understood.

In order to understand the physics of the dynamic amplification of the structural response, indentation tests with stationary towed cylinders have been carried out in the past (Määttänen, 1983; Tsuchiya et al., 1986). These tests confirmed the theory proposed by Blenkarn (1970) that the ice structure interaction process at an interval of the indentation velocities is characterized by an ice force that decreases with increasing stress rate or indentation velocity. The severe structural vibrations occurring at these velocities are considered to be self-excited due to the so-called negative damping. The latter term reflects the observed descending character of the force-velocity dependence.

This paper introduces an experiment that seems to be new in the field of ice engineering. In this experiment added mass and added damping during dynamic ice structure interaction are identified by measuring the dynamic ice load on a cylinder whose motion is displacement-controlled. Though possibly new to the ice engineering community, such experiments are commonly used in offshore engineering for the identification of the added mass and added damping that the fluid load exerts on vibrating submerged pipelines.

The force on a vibrating structure in fluid is often interpreted in terms of the added mass and adding damping. These quantities characterize the parts of the force that are, respectively, in phase with the acceleration and with the velocity of the structure. To measure these, forced vibration tests are usually performed. "Typically, for forced vibration experiments, the Fourier coefficients of the in-line and cross-flow forces are determined at the frequency of forced vibration, as it is assumed that during lock-in the flow forces oscillate at the frequency of cylinder motion" (Ogink et al., 2010). Results of the analysis can be plotted as function of the frequency of forced vibration where for each Fourier coefficient a number of curves are given, each corresponding to a chosen amplitude of forced vibration. An overview of modelling and experiments of vortex-induced vibration of circular cylinders containing the general approaches used in this field can be found in Gabbai (2005). The mayor contributions on forced vibration experiments are the ones by Sarpkaya (1978) and Gopalkrishnan (1993).

The similarities between the observed frequency lock-in in ice structure interaction and the lock-in phenomenon in fluid-structure interaction led to the idea that identification of added mass and added damping parameters for ice-structure interaction might enable better understanding of the complex process of the dynamic ice-structure interaction. For this reason small scale forced vibration tests were performed and a first attempt was made to identify the added mass and added damping parameters. This paper outlines the theory of determination of these parameters,
the experiments carried out, results of the data analysis performed and a discussion of the used approach and results obtained. More information about the Deciphering Ice Induced Vibrations test campaign, the framework in which these tests were carried out, can be found in Määttänen et al. (2012) and additional results on modal analysis in ice structure interaction in Nord (2012).

2. Theory of Determination of Added Mass and Added Damping

Under the assumption that during lock-in the structure oscillates harmonically, the major energy exchange between ice and the structure will take place at the spectral component of the force that oscillates with the same frequency. Therefore, it is reasonable to focus the attention on this force component and interpret it in terms of the added mass and added damping coefficients.

Forced vibration tests are carried out using a rigid model for the structure and forcing it to oscillate with a controlled amplitude and frequency. During the tests the force acting on the structure and its displacement are simultaneously measured at the ice action point. The obtained force signal can be analyzed to show the components in phase with the velocity and acceleration of the structure, which represent the added mass and added damping of the ice during ice-structure interaction respectively.

Without loss of generality, the co-ordinate of the structure can be described by:

\[ U_{\text{forced}}(t) = A_{\text{forced}} \sin(\omega_{\text{forced}} t), \]  

where \( A_{\text{forced}} \) and \( \omega_{\text{forced}} \) are the amplitude and angular frequency of the forced motion. The reaction force on the structure to this motion, \( F_{\text{meas}}(t) \), is measured in the tests. The spectral component of this force at the frequency of the cylinder is characterized by the following two expressions:

\[ F_{\sin}(\omega_{\text{forced}}) = \frac{2}{T_s} \int_{t_0}^{t_0 + T_s} F_{\text{meas}}(t) \sin(\omega_{\text{forced}} t) \, dt, \]  

\[ F_{\cos}(\omega_{\text{forced}}) = \frac{2}{T_s} \int_{t_0}^{t_0 + T_s} F_{\text{meas}}(t) \cos(\omega_{\text{forced}} t) \, dt, \]

where \( F_{\sin}(\omega_{\text{forced}}) \) is the part of the force signal in phase with the acceleration of the cylinder and \( F_{\cos}(\omega_{\text{forced}}) \) is the part in phase with the velocity. \( T_s \) is defined as:

\[ T_s = N T_{\text{forced}} = N \frac{2\pi}{\omega_{\text{forced}}} \]

with \( N \) the number of periods in the measured force signal over which it is integrated. Note that though the measured force may be not exactly periodic, Eqs. [2] and [3] characterize the chosen spectral component of the force rather accurately.
As long as the motion of the cylinder is purely sinusoidal, the added mass can be determined from the component of the force in phase with the acceleration, Eq. [2], resulting in:

\[ M_{\text{added}}(\omega_{\text{forced}}) = -\frac{F_{\text{forced}}}{A_{\text{forced}}\omega_{\text{forced}}} \sin(\omega_{\text{forced}}) \]  

[5]

Similarly, the added damping can be determined from the component of the force in phase with the velocity, Eq. [3], resulting in:

\[ C_{\text{added}}(\omega_{\text{forced}}) = -\frac{F_{\text{forced}}}{A_{\text{forced}}\omega_{\text{forced}}} \cos(\omega_{\text{forced}}) \]  

[6]

3. Forced Vibration Experiments

In the attempt to identify the added mass and added damping of ice in interaction with an oscillating structure, forced vibration experiments were carried out at the Hamburg Ship Model Basin (HSVA) testing facility in August 2011. The tests were carried out as part of the Deciphering Ice Induced Vibrations (DIIV) test program performed in the Research Infrastructure ARCTECLAB in the framework of the integrated infrastructure initiative HYDRALAB-IV.

The test setup, of which a graphic representation and a picture are shown in Fig. 1, consisted of a rigid vertical beam with a cylindrical shape at the ice level. The beam was equipped with a tactile sensor at the ice level in order to measure the global and local pressures on the structure. About one third from the top of the structure it was rigidly connected to a velocity controlled actuator used to force the beam into a sinusoidal displacement pattern with a predefined amplitude and frequency. The beam was furthermore equipped with two laser sensors measuring its displacement near the ice action point and near the hinged support. By simultaneous measurement of the force and displacement at the ice-action point the required input for the analytical post-processing was acquired. Määttänen et al. (2012) gives more details about the test setup used during the Deciphering Ice Induced Vibrations test campaign.

The amplitude of vibration \( A_{\text{forced}} \) and the velocity of indentation \( V \) were controlled. Amplitudes were varied from 0.05\( D \) up to 0.3\( D \), with \( D \) the structure diameter, and the velocity of indentation was varied between 0.01 m/s and 0.1 m/s. The original setup was designed to test for indentation velocities between 0.01 m/s and 0.3 m/s but during the test it showed that when exceeding velocity of 0.1 m/s the actuator control became over-saturated no longer being able to support the desired forced motion to the structure to any extent.

In order to choose the frequencies of vibration the requirement was set that the ice should always be in contact with the structure, i.e. no gap should exist between the ice edge and the structure. The following estimation was made in order to determine such frequencies. Assume that the test structure was pushed into the ice by a carriage resulting in its position given by:
The velocity of the structure then is found by taking the derivative with respect to time of Eq. [7]:

\[ V_{\text{forced}}(t) = V + \omega_{\text{forced}} A_{\text{forced}} \cos(\omega_{\text{forced}} t) \]  

[8]

As follows from Eq. [8], the maximum indentation velocity occurring is equal to \( V + \omega_{\text{forced}} A_{\text{forced}} \) and the minimum indentation velocity occurring is equal to \( V - \omega_{\text{forced}} A_{\text{forced}} \). A negative indentation velocity means that contact is lost between the ice and the structure, therefore the minimum velocity must always be larger or equal to zero resulting in:

\[ \omega_{\text{forced}} \leq \frac{V}{A_{\text{forced}}} \]  

[9]

It was chosen to set the frequency equal to \( \frac{V}{A_{\text{forced}}} \) during the tests performed.

The resulting test matrix for which the tests were executed is shown in Table 2 where frequencies indicated with a * indicate tests which were performed twice. Remaining relevant test parameters are given in Table 1.
Table 1. Relevant test parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure diameter at waterline $D$</td>
<td>220 mm</td>
</tr>
<tr>
<td>Ice thickness $h$</td>
<td>60 mm</td>
</tr>
<tr>
<td>Average temperature of the ice</td>
<td>-2 °C</td>
</tr>
<tr>
<td>Laser resolution</td>
<td>100 Hz</td>
</tr>
<tr>
<td>Tactile sensor resolution</td>
<td>22.6 Sensels/cm²</td>
</tr>
</tbody>
</table>

Table 2. Test matrix showing amplitude of vibration at ice action point, velocity of indentation and frequency of vibration for which the tests were carried out. Frequencies indicated with a * correspond to tests which were performed twice.

<table>
<thead>
<tr>
<th>$A_{\text{forced}}$ [mm]:</th>
<th>11</th>
<th>22</th>
<th>44</th>
<th>66</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V$ [mm/s]:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.145</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>0.289</td>
<td>0.145</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>0.434</td>
<td>0.217</td>
<td>0.109</td>
<td>0.072</td>
</tr>
<tr>
<td>40</td>
<td>0.579*</td>
<td>0.289*</td>
<td>0.145*</td>
<td>0.096*</td>
</tr>
<tr>
<td>50</td>
<td>0.723*</td>
<td>0.362*</td>
<td>0.181*</td>
<td>0.121*</td>
</tr>
<tr>
<td>60</td>
<td>0.868</td>
<td>0.434</td>
<td>0.217</td>
<td>0.145</td>
</tr>
<tr>
<td>70</td>
<td>1.013*</td>
<td>0.506*</td>
<td>0.253*</td>
<td>0.169</td>
</tr>
<tr>
<td>80</td>
<td>1.157</td>
<td>0.579</td>
<td>0.289</td>
<td>0.193</td>
</tr>
<tr>
<td>90</td>
<td>1.302</td>
<td>0.651</td>
<td>0.326</td>
<td>0.217</td>
</tr>
<tr>
<td>100</td>
<td>1.447</td>
<td>0.723</td>
<td>0.362</td>
<td>0.241</td>
</tr>
</tbody>
</table>

4. Obtained Data

The obtained data consists of time traces (row data) of the ice load and displacement for each of the test cases from Table 1. The global ice load is found by integration of the local pressures, obtained from the tactile sensor data, over their respective area of action. For each pressure area the component in the direction of forced motion is taken into account to correct for the fact that the pressures are measured normal to the surface of the cylinder. A dynamic friction coefficient of 0.1 is used to account for the friction between ice and the outer steel surface of the cylinder.

One set of the obtained displacement and force signals is shown unaltered in Fig. 2. During and after the tests several problems were encountered influencing the results of the intended analysis. The problems encountered and the attempted solutions are discussed in the following paragraphs. Fig. 3 shows the effect of the described modifications on the original signals shown in Fig. 2.

- The tactile sensor measurements and laser displacement measurements were facilitated by two different computers and were started at different time moments resulting in a loss of synchronization in time between the force and displacement signals, as indicated by arrow 1 in Fig. 2. Also the durations of the signals are unequal. This problem is solved by visually inspecting both the displacement signal and the force signal and synchronizing the point of first failure, the point where the indentation was stopped and the points of major ice failure. Because the phase shift between the force and displacement signal is of
key importance to the determination of added mass and added damping, this procedure resulted in a small loss of quantitative accuracy of the results.

- The large ice load caused the actuator to slip upon first contact resulting in a shift of the equilibrium position of its motions as can be seen by arrow 2 in Fig. 2. This affects the mean displacement of the structure, but does not affect the results significantly as the amplitude and frequency of forced vibration remained approximately equal to the desired ones. In order to obtain a sinusoidal signal with a zero mean value for the displacement, the signal is shifted up or down, depending on the direction of the occurring slip, over the range where the interaction is present.

- The large ice load also caused the acceleration of the structure to be not exactly as the actuator was incapable of maintaining this. This affects the analysis significantly as for a non-sinusoidal motion of the cylinder the method described in Section 2 of the paper cannot be applied directly. Therefore it has to be concluded that also here a loss of quantitative accuracy of the results is obtained. However, since the periodicity and amplitude of the motion are approximately maintained an identification of the sign of the added mass and added damping is still considered to be possible. In order to account for the changed displacement signal the method of obtaining the added stiffness and added damping is altered as shown in section 5.

- In some of the cases the measuring range of the laser sensors showed to be insufficient to record the large occurring displacements. This happened when the slip of the actuator became very large resulting in a large offset of the mean displacement. For some of the cases the identification of added mass and added damping can still be performed as only one of the two lasers showed to be out of range. The remaining cases cannot be used for further analysis and are therefore discarded. The reduced test matrix containing only the results which could be used for the analysis is shown in Table 3.

**Table 3.** Reduced test matrix showing amplitude of vibration at ice action point, velocity of indentation and frequency of vibration of the tests for which the added mass and added damping components can be computed approximately. Frequencies marked with a * have two signals which were used.

<table>
<thead>
<tr>
<th>$A_{\text{forced}}$ [mm]:</th>
<th>11</th>
<th>22</th>
<th>44</th>
<th>66</th>
</tr>
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<td>$V$ [mm/s]:</td>
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<td>40</td>
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<tr>
<td>50</td>
<td>0.723*</td>
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</tr>
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<td>70</td>
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<td></td>
</tr>
<tr>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 2. Obtained unformatted displacement and force signal for one test. Test characteristics: $V = 40 \text{ mm/s}$, $A_{\text{forced}} = 11 \text{ mm}$, $f_{\text{forced}} = 0.579 \text{ Hz}$. Arrow 1 shows the shift in time synchronization between the tactile sensor and laser sensor files. Arrow 2 shows the slip of the actuator after first contact with the ice causing a shift of the mean displacement of the structure.

Figure 3. Part of the resulting displacement and force signal after application of adjustments and corrections on the raw data of Fig. 2.
In order to obtain the global load, the local loads obtained from the tactile sensor data are summed up with respect to their components in the direction of forced vibration of the structure. Because the orientation of the tactile sensor with respect to the direction of vibration is not exactly known this summation cannot be performed accurately. This influences the magnitude of the obtained values for added damping and added mass, but is not thought to influence the sign of the added mass and added damping as the global pattern of the load can still be obtained and synchronized correctly in time.

Concluding this section it can be stated that it seems to be impossible to extract quantitatively correct values for the added mass and added damping using the data obtained from this series of experiments. It is however considered possible, using the adjustments to the data as described above, to identify possible trends and to identify if negative added mass and/or added damping is values exist.

An example of the final corrected signal on which the data analysis is performed is shown in Fig. 3. This signal is extracted from the raw signal shown in Fig. 2 by application of the above mentioned adjustments, correcting the displacement output of the laser sensors for their offset with respect to the ice action point and changing the sign of the values of the obtained forces as they were measured in an inverted coordinate system.

5. Identification of Added Mass and Added Damping from Test Results

The displacement signals obtained from the experiments are not completely sinusoidal. To take this into account the general approach to the identification of the added mass and added damping, as discussed in section two, is modified. First the part of the measured displacement signal in phase with the desired sinusoidal displacement signal is calculated:

\[
U_{\text{meas}}(t) \sin(\omega_{\text{forced}} t) dt,
\]

where \(U_{\text{meas}}(t)\) is the measured displacement obtained from the laser signals. For a perfect sinusoidal pattern with the exact forced frequency and amplitude Eq. [10] would give:

\[
U_{\text{meas}}(\omega_{\text{forced}}) = A_{\text{forced}}
\]

For a non-perfect signal a reduced or increased amplitude is found without jeopardizing the phase shift, therefore the parameter \(U_{\text{meas}}\) can be used to give a measure for the resemblance of the actual signal with the perfect sinus. Test series where the difference between \(U_{\text{meas}}\) and \(A_{\text{forced}}\) is considered to be too large (>5%) were removed from the results. The spectral coefficients of the force signal, \(F_{\sin}(\omega_{\text{forced}})\) and \(F_{\cos}(\omega_{\text{forced}})\), are determined by Eqs. [2] and [3]. Using the spectral coefficients of the force signal and \(U_{\text{meas}}(\omega_{\text{forced}})\) the added mass and added damping are determined by:
Fig. 4 shows the obtained values for the added damping as a function of the forced vibration frequency. In this plot only the values for a reduced amplitude equal to 0.05 are given:

\[ A_n = \frac{A_{\text{forced}}}{D} = 0.05 \]  

For other values of the reduced amplitude less than four periods where available for the analysis which results in a non-converged value for the added damping. For this reason the results of these experiments were removed from the dataset.

A trend can be seen in Fig. 4 that below a certain indentation velocity the added damping values become more and more negative. This is in correspondence with the observations from the earlier tests with stationary moving indentors performed by Määttänen (1983) and Tsuchiya et al. (1986). It also confirms one of the main theories used for explaining the occurrence of ice induced vibrations and frequency lock-in, namely the theory of self-excited vibration due to the presence of negative damping.

![Figure 4. Added damping versus velocity of indentation for a reduced amplitude of 0.05.](image)

Fig. 5 shows the obtained values for the added mass as a function of the indentation velocity. For the reasons as described above also only results for a reduced amplitude equal to 0.05 are shown. Values for the added mass are, as the indentation velocity decreases, shown to go from positive and in the order of magnitude of the structural mass, being approximately 100 kg in this test series, towards negative and in orders of magnitude larger than the structural mass. The value
obtained for an indentation velocity of 20 mm/s contains a magnitude error due to the shortness of the time signal available for processing, but this does not affect the general trend observed.

Thus, it is shown that the added mass of the ice can be significant and, depending on the ice velocity, be either positive or negative. This seems to be a novel result which is hoped to contribute to the development of predictive models for dynamic ice-structure interaction.

Naturally, the results reported in this paper need to be confirmed by a new experimental campaign given the difficulties and resulting inaccuracies discussed in Section 4.

**Figure 5.** Added mass versus velocity of indentation for a reduced amplitude of 0.05.

### 6. Conclusion

Forced vibration experiments were carried out in the attempt to identify the added mass and added damping properties of ice during dynamic ice-structure interaction. The test setup consisted of a rigid cylinder equipped with a tactile sensor to measure the ice pressure at the ice-structure interface, and laser sensors to measure structural displacement simultaneously. The structure was forced by a hydraulic actuator to oscillate with a controlled amplitude and frequency.

During the execution of the experiments useful experience has been gained about the key problems which can occur during forced vibration experiments for ice-structure interaction. It showed to be difficult to maintain a perfect sinusoidal forced displacement pattern of the structure, due to the large ice loads on the structure. Also the synchronization of the force and displacement signals in time needs to be done very accurately or must be guaranteed during the experiments in order to obtain accurate predictions of the magnitudes of added mass and added damping. By addressing these issues, future test campaigns will be more successful in obtaining useful data.

The obtained results confirm the negative damping to occur for low indentation velocities as observed in several previous testing campaigns. As a new result it is found that also a significant added mass occurs during ice-structure interaction at low indentation velocities. This added mass
can be both positive and negative. The latter is especially important as it may be one of the main missing links in the theories of the frequency lock-in.

The test campaign, method of analysis introduced and results discussed in this paper provide an excellent basis for a new series of forced vibration experiments which should provide sufficiently accurate data for quantification of the magnitudes of added mass and added damping as functions of the frequency and amplitude of the cylinder vibration.

Acknowledgements
The authors would like to acknowledge the support from the SAMCoT CRI through the Research Council of Norway and all the SAMCoT partners. The work described in this publication was supported by the European Community’s 7th Framework Programme through the grant to the budget of the Integrated Infrastructure Initiative HYDRALAB-IV, Contract no. 261520. The authors would like to thank the Hamburg Ship Model Basin (HSVA), especially the ice tank crew, for the hospitality, technical and scientific support and the professional execution of the test programme in the Research infrastructure ARCTECLAB.

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