POAC'13
Espoo, Finland

Proceedings of the 22nd International Conference on
Port and Ocean Engineering under Arctic Conditions
June 9-13, 2013
Espoo, Finland

THE INFLUENCE OF FRICTION AT THE ICE-STRUCTURE INTERFACE ON ICE INDUCED VIBRATIONS

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ABSTRACT

Vertically-sided offshore structures occasionally experience sustained vibration due to drifting ice sheets crushing against them. These vibrations may lead to problems associated with structural integrity and safety. Traditionally, three regimes of interaction are distinguished: intermittent crushing, frequency lock-in and continuous brittle crushing. These regimes correspond to the dynamic ice-structure interaction at low-, intermediate- and high ice sheet velocities respectively.

In this paper the effect of friction at the ice-structure interface on the frequency lock-in regime is studied. This investigation is a follow-up of a comparison between prediction models and full-scale data for ice induced vibrations which has been carried out in the framework of an Ice Induced Vibrations JIP (IIV JIP). This comparison showed that no simultaneous match could be found for both the structural acceleration of and ice force on cylindrical structures. This raised the question of whether or not the neglected in the models frictional interaction at the ice-structure interface could be a reason for such an inconsistency. In order to answer this question the interaction at the ice-structure interface is implemented, in a simplified manner, according to the Coulomb friction law in one of the models tested in the framework of the IIV JIP. In this model it is assumed that the three regimes of the dynamic ice-structure interaction can be described based on the distribution of ice strength in the ice sheet.

It is concluded that friction alone cannot explain the large inconsistency in case of cylindrical shaped structures. It is suggested that the way the current models translate the available measurement data to input might be worth further investigation. Effects of friction on the range of velocities for which frequency lock-in might occur are expected to be minimal when a fully confined scenario is considered, although an overall increase in loads is predicted. The influence of friction for scenarios with marginal confinement needs further investigation with a more advanced model.

INTRODUCTION

Level ice acting against vertically sided offshore structures is known to cause ice induced vibrations. The first documented cases of these vibrations date back to the late 1960's when Peyton (1968) and Blenkarn (1970) reported on their full-scale observations on oil platforms at the Cook Inlet, Alaska. Since then, many attempts have been made to create models aimed at prediction of the dynamic ice-structure interaction. The most widely applied models nowadays are the model introduced by Määttänen (1999) for slender structures, and the models by Sodhi (1995) and Kärnä et al. (1999) which are applicable for both slender and wide structures. All approaches show to have a potential for use in simulations of dynamic ice-structure interaction. However, predictions of those models often do not match experimental data, which calls for the development of new models of the dynamic ice-structure interaction.

In an attempt to accumulate the available knowledge and data with the aim to develop a design tool that can numerically simulate the dynamic interaction process, the Joint Industry Project entitled “Ice Induced Vibrations” (IIV) has been initiated. The first phase of this project was completed in June 2012 (Kärnä et al., 2013). During this phase several models have been used, both existing and newly developed, and verified against existing data in order to assess their predictive capabilities. In this paper one of the questions which remained after the verification phase is elaborated upon.

The models for ice induced vibrations have been applied to run simulations for comparison with existing publically available and confidential measurement data. The data used corresponded to structures with both rectangular and circular shapes at the ice-action level. From the comparison it was found that the models gave reasonably good predictions for rectangular shaped structures, whereas a discrepancy has been found for all models when circular shaped structures were considered. In this case the structural acceleration could be predicted with sufficient accuracy, but the magnitude of the corresponding ice loads was off more than 100%. This observation raised the question if a mechanism is missing in the models which has a pronounced effect for slender circular structures and is less pronounced for rectangular structures.

One such mechanism could be the in-plane friction at the interface which has been neglected in the applied models. In-plane friction is used here to describe the frictional interaction at the ice-structure interface in the plane of motion of the ice. Existing models do include friction in the vertical direction (Kärnä et al., 1999), but the in plane friction is not taken into consideration. In order to investigate the influence of the in-plane friction on ice induced vibrations, one of the models used for the comparison in the JIP is improved by implementing a simplified frictional interaction according to the Coulomb friction law.

In this paper the reason to investigate the in-plane friction is explained in more detail, and a comparison is made with full-scale. Based on the obtained results a conclusion is drawn as to the influence of in-plane friction on the predicted ice induced vibrations.

MODEL FOR DYNAMNIC ICE-STRUCTURE INTERACTION

A full description of the model used for ice-structure interaction prediction is not given here for reasons of confidentiality. The model is a new development based on the model proposed by Matlock et al. (1971) and an earlier modification by Hendrikse et al. (2011).

The idea that the ice loading is strongly associated with the presence of high-pressure zones (strong points) in ice forms the basis for this model. The three main regimes which are encountered during dynamic ice structure interaction according to ISO19906, 2010 are**:** Intermittent crushing, frequency lock-in and continuous brittle crushing. These regimes differ fundamentally in whether or not the simultaneous (collective) or non-simultaneous failure of these strong points occurs in the course of the dynamic ice-structure interaction.

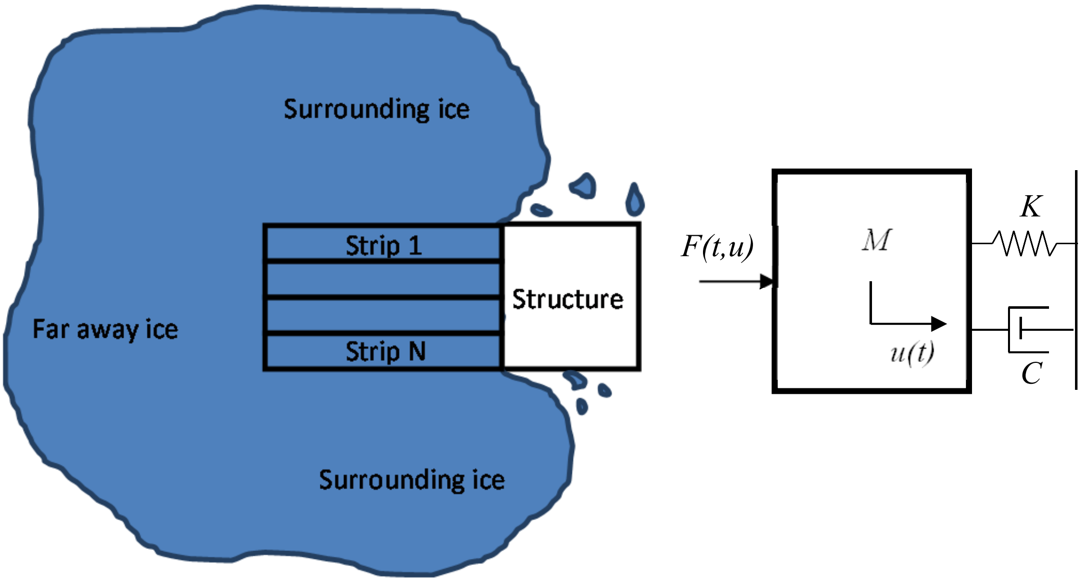

Figure 1. Left: Ice modelled as a system of ice strips. Right: Structure representation by a simple oscillator.

In accordance with this idea the ice is modelled as a system of ice strips, see Figure 1, whose properties reproduce the local failure in the statistical sense (the mean value of the strength and standard deviation of that). Each strip is inhomogeneous and contains a certain amount of strong points, which are characterized by a higher than average value of the crushing strength. The strong points are distributed randomly along the strips. In the regime of intermittent crushing, which occurs at low ice velocities, a number of strong points belonging to different strips have the time to come in contact with the structure before failing together thereby showing the spatial synchronization of the ice failure. This results in a typical saw-tooth pattern of the load. In the regime of frequency lock-in, the behaviour of strong points is similar but the collective failure occurs with a frequency that is close to the natural frequency of the structure. The latter leads to the temporal synchronization of ice failure with the structural vibration, which is called frequency lock-in. In the regime of continuous brittle crushing, which occurs at higher ice speeds, the strong points do not have sufficient time to synchronize and fail independently. This leads to a typical random pattern of the ice load on the structure.

The structure is represented by a simple oscillator as shown in Figure 1**.** The shape is taken to

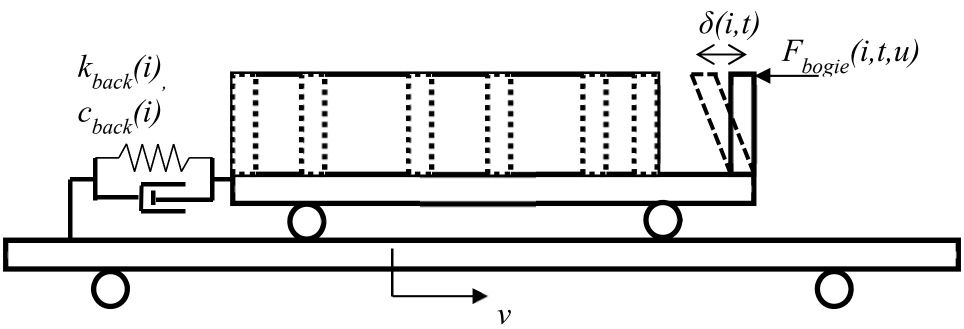

Figure 2. Single ice strip represented as a bogie with distributed strength over the different “teeth” on the top bogie.

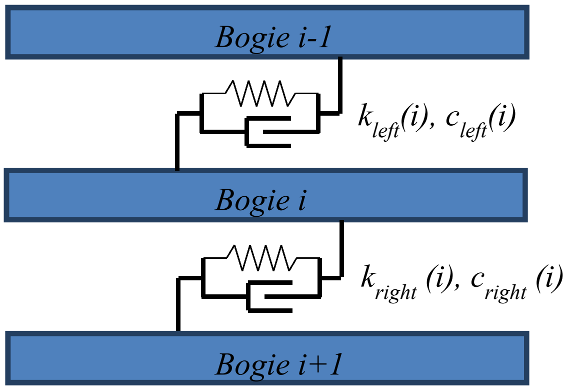

Figure 3. Each bogie is connected to both of its neighbours to allow for spatial synchronization to occur in the model.

be either rectangular or circular where for the latter the non-normal loading is taken into account. Each of the strips is represented by a set of bogies as shown in Figure 2**.** The top bogie consists of a set of teeth which represent the different strong and weak zones in the ice. The mass of the ice in the interaction zone is taken into account as well as the elasticity and viscosity of the far away ice. Between each of the bogies a connection is introduced with springs and dashpots (Figure 3**)** to allow for the spatial synchronization in the intermittent crushing and frequency lock-in regimes. The equations of motion for the system have been implemented in the FORTRAN95 language and are solved in the time domain.

THE REASON TO INVESTIGATE INTERFACE FRICTION

The model as described in the previous chapter has been calibrated with both classified data and data available in open literature. The calibration has been performed in two stages. First a set of laboratory data has been used to tune the free parameters in the model. Afterwards the model was applied to different loading scenarios corresponding to previously unused full scale measurement data. This was done to test the predictive capabilities of the model. Here we present the results in a dimensionless manner as the data is restricted. It has been found that the model produced reasonably good results for the scenarios where a rectangular structure was considered. An example of a comparison with excerpts taken from the Molikpaq May 12, 1986 data (Timco and Wright, 2005) is shown in Figure 4. Note that the data from the model predictions have not been filtered.

Applying the same approach to a slender cylindrical structure however showed some discrepancies. Figure 5 shows the results for the load and acceleration prediction by the model for a data set from the Norstømsgrund lighthouse. It can be seen that the acceleration prediction is quite accurate but the corresponding ice load is over-predicted. There are a couple of reasons which might explain this discrepancy. It could be that the proposed mechanism for ice-structure interaction used in the model is incorrect. Secondly there could be a misinterpretation in the measurement data used. And one other important reason for the discrepancy could be that the way the measurement data is translated into input for the model leads to such over-prediction.

It was chosen to investigate if this “missing link” is a missing mechanism in the form of friction at the ice-structure interface as both this model and other models used in the IIV JIP seemed to predict the loads on rectangular structures much better than on cylindrical structures. Since all models were tuned to laboratory data and

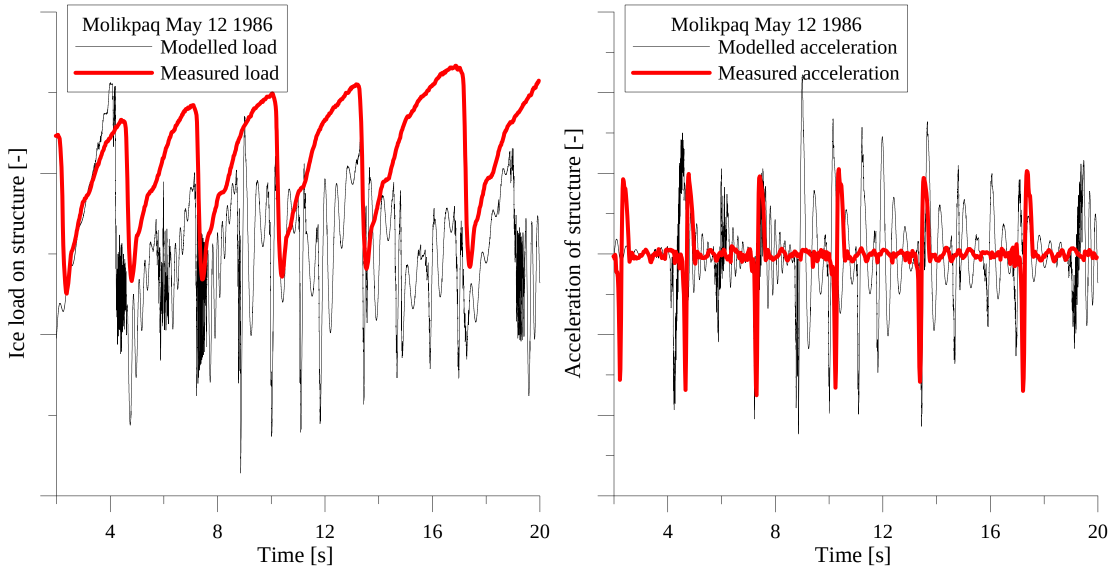

Figure 4. Comparison of predictions and measurements for excerpt of the Molikpaq May 12, 1986 event (Timco and Wright, 2005). Left: Ice load, Right: Acceleration of the structure.

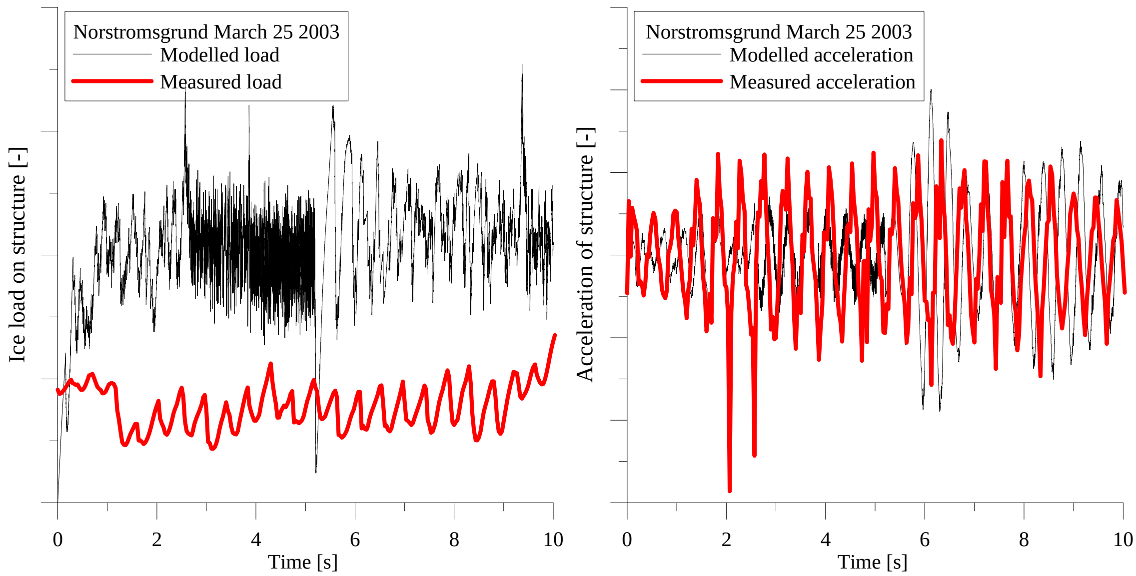

Figure 5. Comparison of predictions and measurements for Norstrømsgrund March 25, 2003 event. Left: Ice load, Right: Acceleration of structure. The difference between mean modelled load and mean measured load in the left figure is a factor two.

performed reasonably well when scaled to full scale data for rectangular structures it seemed plausible that a missing mechanism could be the explanation for the discrepancy.

When an ice sheet crushes against a rectangular structure at one of its faces the effect of the in-plane frictional contact on the motion of the structure in the direction normal to this face can be expected to be minimal. For cylindrical structures the frictional loads can become quite significant in magnitude provided that enough confinement by the surrounding ice exists. Part of the load in the direction of motion of the structure is then caused by friction, which is not measured by the load panels. Identification of the force by just using the load panels therefore would give an under-prediction of the load and could explain why the Norstrømsgrund ice load is over-predicted by the model.

IMPLEMENTATION OF FRICTION IN THE NUMERICAL MODEL

The frictional interaction is added to the model in a simplified manner to avoid having to model the ice motion in multiple directions. The frictional interaction is represented by a friction law that is shown in Figure 6. The friction force is then described by:

$$F_{friction} = \left(F_c + \left(F_{brk} - F_c\right) e^{-cf \cdot v_{rel}}\right) \cdot \mathrm{sign}\left(v_{rel}\right) \tag{1}$$

with F_c the Coulomb friction force, F_{brk} the force at which the interaction regime changes from stick to slip, also called the break-away force. cf is a coefficient that takes into account the descending part of the curve known as Stribeck friction and v_{rel} is the relative velocity between the ice and the structure in the tangential direction. When the break-away force is taken as a static friction factor μ_s times the normal force F_N exerted at the interface between the ice and the structure and the Coulomb friction force is taken as a kinematic friction factor μ_k times the normal force F_N , this relation can be rewritten to:

$$\begin{gathered} F_{friction} = \mu F_N \\ \mu = \left(\mu_k + \left(\mu_s - \mu_k\right) e^{-cf \cdot v_{rel}}\right) \cdot \mathrm{sign}\left(v_{rel}\right) \end{gathered} \tag{2}$$

Determination of the static and kinetic friction coefficients for ice in contact with construction materials is a separate research topic. In this paper values for ice-steel interaction are deduced from recent publications on the topic (Frederking and Barker, 2002., Mills, 2008) and assumed to be given as:

$$\mu_s = 0.05 - 0.2 \;\; (0.5 \text{ when in stick}) \tag{3}$$

$$\mu_k = 0.02 - 0.1 \tag{4}$$

A couple of assumptions need to be made in order to implement this friction law into the model without increasing its complexity in terms of the number of degrees of freedom.
First the interpretation of the tangential relative velocity should be discussed. In reality this velocity is zero when the ice sticks to the structure and should be derived from the dynamic equations when the ice moves along the structure interface. Furthermore, symmetry is assumed such that the resulting forces perpendicular to the direction of motion of the ice are equal to zero.

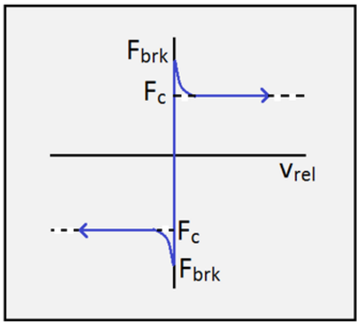

Figure 6. Coulomb friction law implemented in the model.

Under these assumptions the relative tangential velocity between ice and structure along the interface can be expressed in terms of the velocity of ice in the direction of motion of the structure at each point on the interface.

THE EFFECT OF INTERFACE FRICTION ON THE PREDICTED LOAD

The increase in load in the direction of motion of the structure due to friction has been investigated. The coefficients of friction used are μ_s = 0.2 and μ_k = 0.02. It has been found that the increase in load on the structure is on average 15% which corresponds roughly to the static friction coefficient as could be expected for the fully confined scenario considered in the model.

When this maximum static friction is applied over the full width of the structure a significant increase of the ice load is observed. However, the increase is not large enough to explain the discrepancy in the measurements for the Norstrømsgrund lighthouse. Despite the fact that another explanation needs to be found, the effect of friction on the amplitudes of oscillations and the velocities for which frequency lock-in can occur are further considered in the next section.

INFLUENCE OF FRICTION ON THE FREQUENCY LOCK-IN REGIME

The influence of friction on the frequency lock-in regime has been studied. A static friction coefficient of μ_s = 0.2 and a kinetic friction coefficient of μ_k = 0.05 have been used. The results for the standard deviation and mean force are given in Figure 7 and Figure 8. The results take into account the average conditions from ten runs at velocity intervals of 0.01 m/s. From Figure 7 it can be seen that the lock-in regime seems to be unaffected by the frictional interaction. Amplitudes of oscillation are about equal to the case without friction. Figure 8 shows an increase in the mean displacement as expected. This result suggests that for the considered case friction can indeed be neglected, as commonly done in models aimed at the prediction of ice induced vibrations.

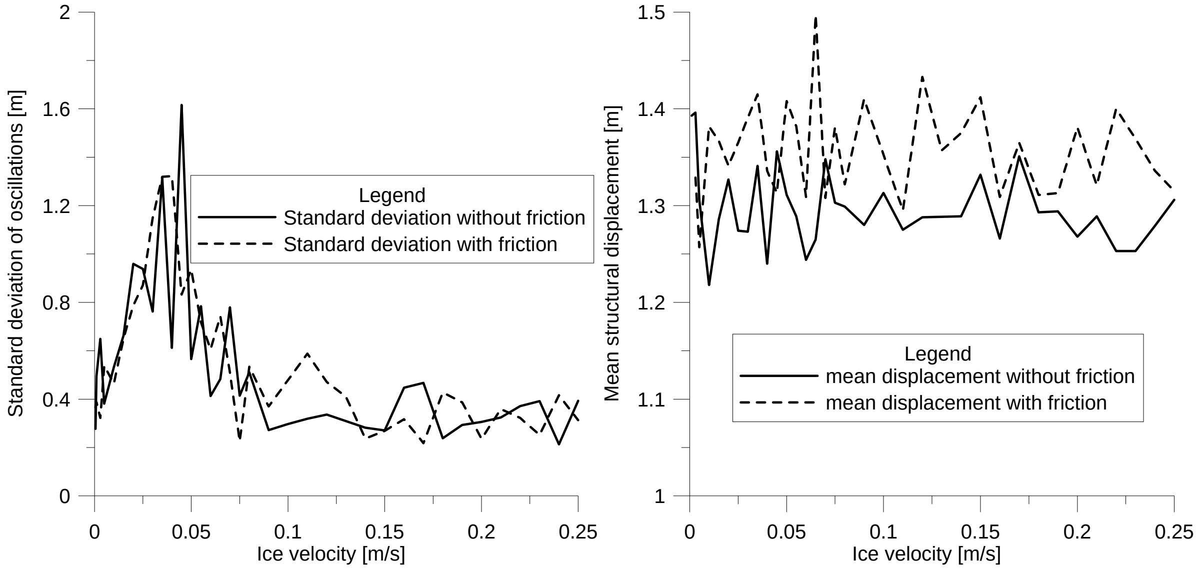

Figure 7. Left: influence of friction on the standard deviation of oscillations. Right: influence of friction on the mean displacement. The frequency lock-in regime is found to be in the range of 0.01 m/s up to 0.06 m/s.

THE NORSTRUMSGRUND CASE

The problems with the prediction of the Norstrømsgrund lighthouse cases have not been solved by application of the interface friction only. After a more detailed analysis the best fit to the data was obtained by assuming that the global compressive strength of the ice at the location was half of that of the uniaxial compressive strength of ice actually measured at that specific location. The model predictions for the acceleration and ice load taking into account the friction in this case give the results as shown in Figure 8. An interesting point to note is that without taking frictional forces into account the match for the loads is significantly worse. It would be interesting to check if information about the frictional loads is available from the Norstrømsgrund data. A study on this topic might reveal the answer to the questions of load over-prediction by the models.

It remains to be said that the physical mechanism for the occurrence of load synchronization and frequency lock-in is still not fully understood. Therefore the large discrepancy could just be a result of some other physical phenomenon missing in the model. Furthermore the way the uniaxial compressive strength of ice is used in the model might contain part of the solution. A value for the uniaxial compressive strength is used in both cases to represent fully confined ice. This however fully disregards any size or scaling differences which one might expect to exist for a multi-year flow and a first-year flow. Such questions require more modelling in order to be answered, something which should be undertaken in the future.

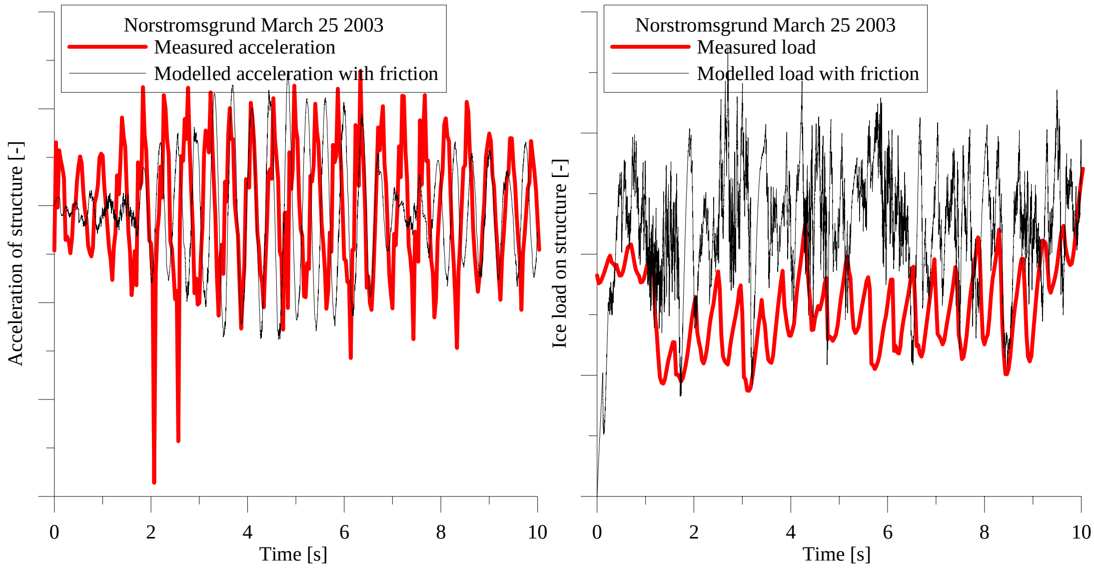

Figure 8. Prediction of acceleration (left) and load (right) on the Norstrømsgrund lighthouse with decreased ice strength and pure static friction forces taken into account.

DISCUSSION

In order to answer the question about the importance of contact-friction on ice induced vibrations a more advanced analysis is necessary than that presented in this paper. Detailed modelling of contact and friction problems requires multi-dimensional numerical models which are not readily available. It was chosen not to develop such a model but to investigate the potential influence of friction at the ice-structure interface first with simpler approximate models. The main drawback of this approach is the over-simplification of the interaction process.

The first factor which has not been included is the effect of confinement. The current model assumes full confinement which results in frictional forces to be quite low relative to the normal loads. When investigating scenarios with a reduced confinement this ratio might be significantly changed and the effects of friction might become more dominant in the process. The same holds for the confinement in vertical direction which increases with increasing roughness of the contact surface. Such effects should be considered in order to simulate or model the interaction process at a wide range of ice pack conditions.

Secondly, the stick-slip phenomenon which occurs in systems with Coulomb friction has been over-simplified in this study. It has been observed in a previous study that stick-slip interaction can cause a response similar to frequency lock-in. However stick-slip alone does not explain the three interaction regimes occurring in the dynamic ice-structure interaction. Advanced multi-dimensional models should include the frictional interaction in order to investigate its effect on the frequency lock-in regime in more detail.

Despite the above discussed drawbacks of the chosen approach, the results presented in this paper provide a basis for discussion of the physical understanding of the interaction process and the importance of friction for the ice induced vibrations.

CONCLUSIONS

A model for the prediction of ice induced vibrations has been validated against existing full-scale data. The model has shown to be capable of predicting ice loads on, and structural accelerations of, rectangular structures within acceptable ranges. For cylindrical structures the acceleration was predicted within acceptable accuracy, whereas the corresponding ice load signal was overestimated by more than 100%.

In search for a potential reason for this overestimation of the ice load, the effect of friction at the ice-structure interface on cylindrical structures has been investigated. Analysis showed that the maximum increase in ice load is in the range of 15% for the chosen coefficients of friction.

The effect of friction on the range of velocities over which frequency lock-in might occur is investigated in an approximate manner, as well as the corresponding amplitudes of structural oscillations. For relatively small friction coefficients, it is suggested that frictional interaction needs not to be taken into account when the aim is to investigate the frequency lock-in regime. For larger friction coefficients the stick-slip interaction might have a significant influence on the frequency lock-in regime and amplitudes of oscillation. It is therefore suggested that models aimed at the prediction of ice induced vibrations should distinguish between these cases.

The question about the influence of friction at the ice-structure interface has not been answered. However it is shown that the physical understanding of the dynamic ice-structure interaction process is still lacking. This investigation provides a basis for discussion about the need to model this interaction process in multiple dimensions and the need to include friction at the ice-structure interface in such models.

ACKNOWLEDGEMENTS

The authors would like to thank the partners in the Ice Induced Vibrations JIP for granting the permission to publish this paper: Karna Research & Consulting, Dr.techn. Olav Olsen, Statoil, Delft University of Technology, Concrete Structures, Shell, BP, Exxon-Mobil, Conoco Philips, ABS, GustoMSC and independent consultants D. Sodhi and M. Jeffries.

The authors would like to acknowledge the support from the SAMCoT CRI through the Research Council of Norway and all the SAMCoT partners.

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