ICE MODEL TESTS WITH A CYLINDRICAL STRUCTURE TO INVESTIGATE DYNAMIC ICE-STRUCTURE INTERACTION

G. Onken[1,2], K.-U. Evers[2], A. Haase[2] and P. Jochmann[2]

[1]Institute of Mechanics and Ocean Engineering, Hamburg University of Technology, Hamburg, GERMANY

[2] Hamburg Ship Model Basin (HSVA), Hamburg, GERMANY

ABSTRACT

A physical analogous model of the lighthouse Norstrømsgrund has been built and tested in a series of model tests in ice at HSVA. The dynamic behavior of the lighthouse is simplified as a SDOF-system (single degree of freedom) by translational displacement in the ice plane, which is found to be justified by full scale data.

The model's natural frequency and stiffness are adjustable by correct choice of springs and additional mass. Several tests have proven the accuracy of adjustability.

Stiffness as well as mass is subject to physical constraints, e.g. a minimum mass which can not be fallen short of and a maximum feasible stiffness. Due to these limitations, the model's stiffness had to be reduced. A reasonable approach to convert measured accelerations from model tests to the less compliant full scale structure has been found and used for the model test results. Several events of ice-induced vibrations have been observed. Measured forces and accelerations during dynamic ice-structure interaction at model scale are in good agreement with full scale measurements.

The test set-up is suitable to provide realistic results on the dynamic behavior of cylindrical offshore structures. The paper describes the design of the test set-up, instrumentation and calibration, performance and analysis of conducted tests, and general findings.

INTRODUCTION

Offshore structures located in areas with sea ice formation experience high ice load and acceleration in case of ice-induced vibrations. These vibrations are amplified by dynamic ice-structure interaction, but despite extensive research during the last decades (see e.g. Eranti (1992), Määttänen et al. (1987; 2012), Izumiyama et al. (1994)), their basic mechanism is not completely understood to date (Guo, 2012). This aggravates a numerical modelling of ice-structure interaction.

The project "Breaking the Ice (BRICE)", worked on in 2011 to 2014 by HSVA (The Hamburg Ship Model Basin), Fraunhofer IWES (Fraunhofer Institute for Wind Energy and Energy System Technology) and VTT (Technical Research Centre of Finland), concentrates on the development and verification of new methods to design numerical and physical models for the study of dynamic ice-structure interaction. For this purpose, a compliant physical test set-up is designed at HSVA, which shall be applicable to various offshore structures. As a first application, a cylindrical model with the geometry and dynamic behavior of Norstrømsgrund lighthouse is tested.

ANALYSIS OF NORSTRØMSGRUND MEASUREMENTS

To identify required model parameters, 44 selected full scale measurements of ice-induced vibrations taken at Norstrømsgrund lighthouse during the STRICE project (Measurements on Structures in Ice, www.strice.org) are analyzed with respect to their intensity, direction of response and number of frequencies involved. Vibration events are categorized as either frequency lock-in, resonant or random vibrations. For this work, resonant vibrations are defined as oscillations in one or more of the structure's natural frequencies and a similar loading rate. Frequency lock-in is a resonant vibration with constantly high amplitudes for at least 5 cycles, and random vibrations are characterized by a broadband spectrum of load and response.

The following conclusions were drawn:

- The largest amplitudes of response arise at frequency lock-in and resonant vibrations.
- The majority of severe vibrations occur in the first natural frequency only, and the magnitude of measured acceleration tends to decrease with an increasing number of frequencies involved in the response (Fig. 1). Therefore, the representation of the first natural frequency is inevitable while additional natural frequencies may be neglected.
- Due to the high stiffness in ice plane, the rotation of the structure caused by bending is negligible as the corresponding rotation angle is small as has no significant impact on the interaction of structure and ice.
- Structural response during lock-in and resonant vibrations follows the ice drift direction (Fig. 2). Hence, one degree of freedom is sufficient to represent the most severe vibrations.

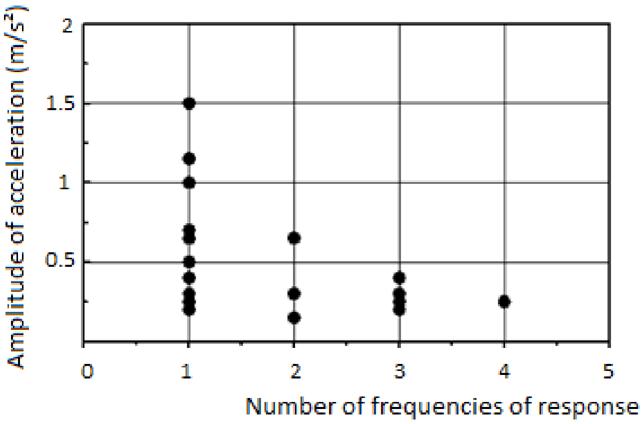

Figure 1. Amplitude of acceleration in ice plane plotted against number of frequencies involved in the response. Only resonant and lock-in vibrations are taken into account.

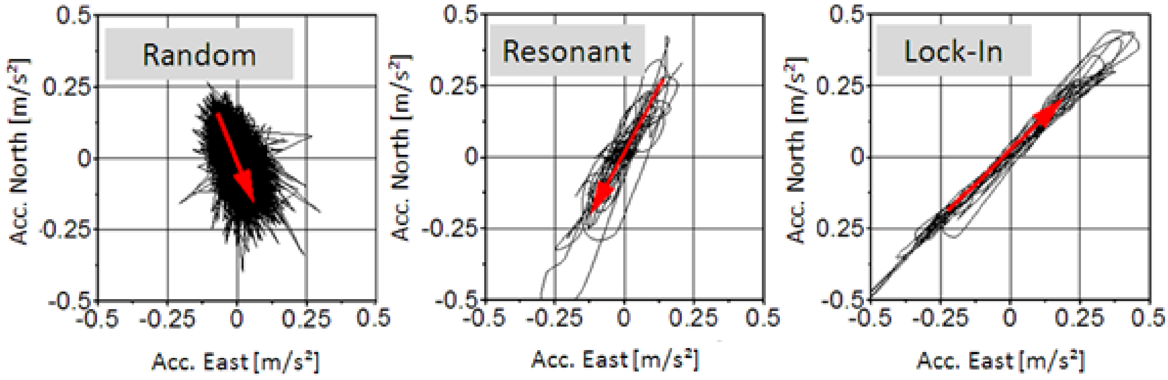

Figure 2. Acceleration in north and east direction, illustrating typical shapes of response found at lighthouse Norstrømsgrund. The arrow demonstrates the ice drift direction.

PHYSICAL COMPLIANT MODEL

Basic principle

A limited number of model test investigations on ice-induced vibrations of offshore structures have been conducted during the last decades. Two different approaches have been used so far: Modelling the full elasticity of the whole structure (Cornett and Timco, 1997) and using a rigid structure with a compliant basis (e.g. Barker et al., 2005). For the present tests the second approach is implemented. The dynamics of the structure are simplified to translational movement in ice drift direction (SDOF model). By splitting the system into a rigid model and a compliant basis with adjustable stiffness and natural frequency, it can be used for different applications in the future. The compliant basis consists of a movable mounting carriage and a rigid basis connected to the basin's floor (Fig. 3). The mounting carriage's compliance is provided by mechanical pressure springs.

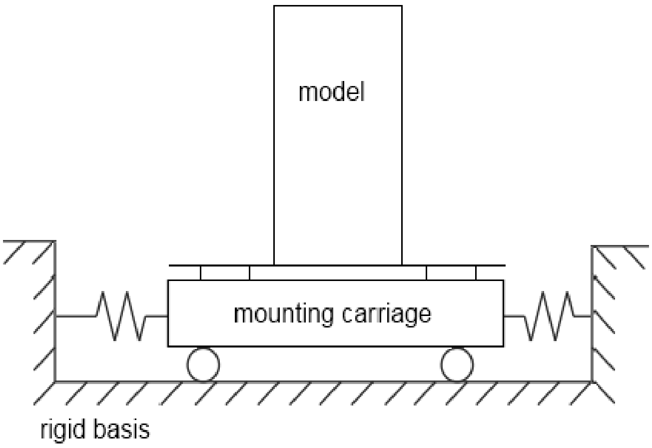

Figure 3. Schematic illustration of the SDOF model.

The natural frequency f_n of such a system is given by

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \quad (1)$$

with k being the translational stiffness and m the oscillating mass. Hence, the structure's natural frequency is adjustable by mass variation at a prescribed stiffness.

Scaling

According to current ice modelling practice, the lighthouse is scaled by Froude and Cauchy scaling law (Timco, 1984). A scale factor of λ=8.7 is used in order to have feasible geometric properties and ice thickness. Unfortunately, using this scale factor requires such high stiffness that it is physically not implementable due to flexibilities of the model itself, the basis and the load cells connecting mounting carriage and model (see Fig. 4). Furthermore, an oscillating mass of more than 3000 kg would be required, which cannot be handled in the basin. Increasing λ is not suitable because of increasing scale effects, and resulting deflections would be small and hardly measurable. To overcome this problem, it is decided to reduce the system's stiffness to a feasible value but keep the natural frequency scaled correctly.
An increase of structural compliance may have an impact on the occurrence of frequency lock-in, velocity-dependent failure mode and ice load as examined for example by Kamesaki et al. (1996). These topics have to be discussed when model test results are analyzed.

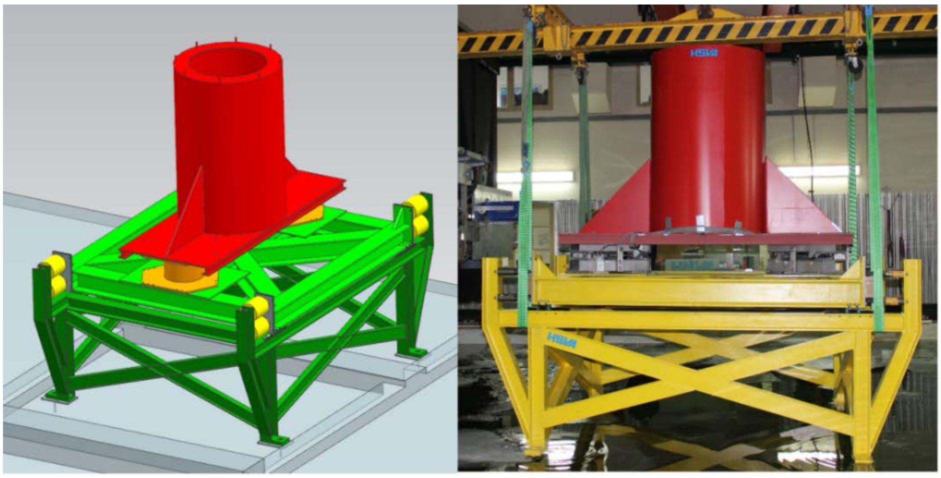

Figure 4. Construction drawing (left) and photo of practical implementation of the SDOF model (right).

The physical implementation is shown in Fig. 4. Its properties are given in Tab. 1. Full scale parameters are taken from STRICE reports and tiltmeter measurements conducted by Frederking (2005). Natural frequencies are identified by decay tests conducted inside the basin.

Table 1. Physical properties of the test setup.

Physical parameter	Physical model	Full scale structure
Diameter (m)	0.83	7.2
Translational stiffness in ice plane (N/mm)		
- ice drift direction	3195	850000
- crosswise	990	850000
Dominant natural frequency (Hz)	8.1	2.6
Damping (%)	6	4 - 5

The physical test set-up has one significant deficiency: a high flexibility crosswise to the ice drift direction. This stiffness has to be magnified for future applications, which was not possible for the present tests because of the limitation of structural mass by Eq. 1.

Adjustability of natural frequency by stiffness and mass variation

Dry tests with different stiffness and mass are conducted to prove the applicability of Eq. 1. Results are shown in Tab. 2. These tests are carried out using rigid basis and mounting carriage only, with no model fixed to it. This prevents the influence of additional flexibilities caused by the model. The stiffness is measured by static deflection of the mounting carriage. The pulling force is recorded using a load cell and the resulting deflection is measured by lasers. The natural frequency is calculated by spectral analysis of the structure’s movement after a sudden release from the deflected position.

Table 2. Overview of test results with different mass and stiffness.

Parameter	Configuration 1	Configuration 2	Configuration 3
Oscillating mass (kg)	1329.6	1571.6	1571.6
Stiffness (N/mm)	5110	5110	2835
Number of tests	5	6	5
Mean actual frequency (Hz)	10.22	9.08	6.78
Theoretical frequency according to Eq. 1 (Hz)	9.87	9.07	6.76

MODEL TEST PROCEDURE

A series of tests is conducted in the large ice tank at HSVA. Four ice sheets with two different ice thicknesses and similar bending and crushing strength are each divided into smaller sheets (each 10 m length) and piece by piece pushed against the fixed structure by the towing carriage. By pushing the ice against the structure instead of vice versa, closed-loop control oscillations from the carriage do not affect the measurement, and the basis of the structure can be build more rigid.

Thickness and ice strength are chosen according to full scale data of severe vibration events. Flexural strength of 70 kPa model scale (ms) and thickness of 33 to 50 mm (ms) are intended. The test matrix is given in Tab. 3. Two 6-component scales connect the model and the mounting carriage to measure the ice load. Two lasers in x- and y-direction and an inertia measurement unit (IMU) are used to record the structure's movement.

Three ramp velocity tests with a constant acceleration of 2 mm/s² are conducted to study the velocity dependent failure modes. All other tests are done with constant velocity, based on observations made during previous test runs. In total, 16 test runs with 20 different combinations of ice drift velocity and ice thickness are carried out.

Table 3. Test matrix. Values given in model scale (ms) and full scale (fs).

Sheet	Ice thickness ms (mm)	Ice thickness fs (mm)	Drift velocity ms (cm/s)	Mean flexural strength ms (kPa)	Mean compressive strength ms (kPa)
01	33	286	5 – 15 (ramp)	71.5	141
02	32.5	282	8; 9; 11; 1 – 4 (steps)	61	100
03	33.5	290	1 – 4; 5 - 6 (steps) 0.5; 1; 4; 15	73	123
04	48.6	442	1 – 4; 5 –6; 2 – 3 (steps) 15	65	114

RESULTS AND DISCUSSION

Ice failure modes

Different failure modes have been observed during the tests. At low velocities (1 – 3 cm/s), the ice failed mostly in local bending failure with no significant dynamic forces acting on the structure. To evaluate this result, it has to be considered that the friction coefficient of the model amounts to approximately μ=0.09, thus significantly less than the friction on the concrete lighthouse walls. At 3 to 4.5 cm/s, the failure mode changed to intermittent crushing with simultaneous failure, inducing several severe vibrations. Persistent continuous crushing has only been observed once (Run 04400) at 15 cm/s; in between these velocities the ice failed non-simultaneously in a mixed mode with periods of continuous crushing, interrupted by bending and buckling failure.

Calculation of ice load

The ice load F_{ice} has to be calculated from the load F_s recorded by the 6-component scales. F_s summarizes the external ice force, inertia forces due to the acceleration of the structure and viscous forces related to the structure's velocity. Viscous forces are small compared to ice load and inertia forces and therefore negligible:

$$F_{ice} = F_s - a \cdot m \tag{2}$$

The oscillating mass consists of structural and added hydrodynamic mass and is taken from decay tests conducted inside the basin. The added mass provided by ice is not taken into account, as its magnitude is not measurable with the chosen test set-up and no reliable prediction method is available yet. Research on this topic was done recently by Hendrikse et al. (2012).

An example of measured and calculated force components is given in Fig. 5.

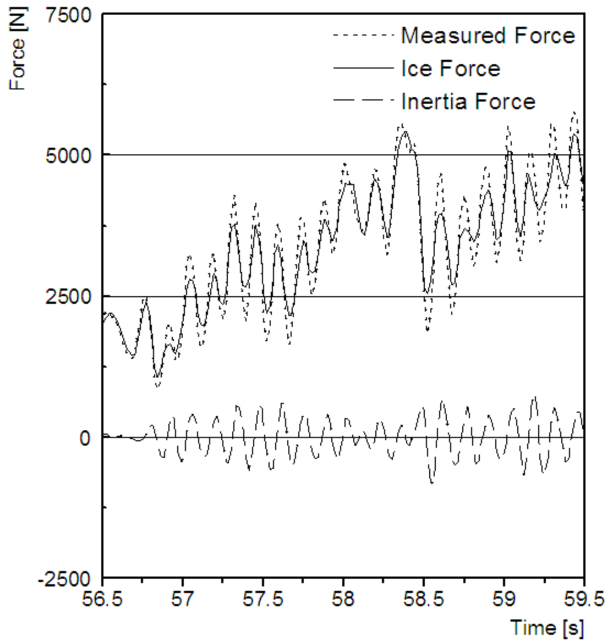

Figure 5. Example of measured and calculated forces during resonant vibrations (Run 04400).

Validation against full scale data

As stiffness of model and full scale structure crosswise to the ice drift direction are not similar, only a limited number of observed vibration events can be compared to full scale data. Events are comparable if the direction of response coincides with the ice drift direction and no other than the first dominant natural frequency of the model is involved in the response. Hence, only resonant vibrations can be used for validation. From 39 observed ice-induced vibrations, 6 vibration events meet these criteria, which are also the most severe vibrations observed during the tests. They oscillate in frequencies 5 – 10% lower than the natural frequency and have 6 to 16 constant amplitudes of response. This interval of frequencies corresponds to observations made by other authors (e.g. Kärnä, 1994). Fig. 6 shows an example of analyzed vibrations.

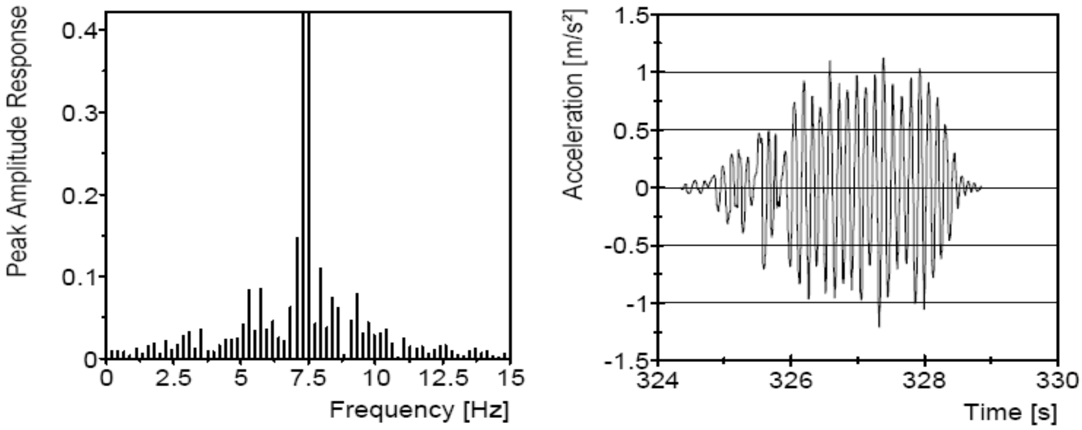

Figure 6. Measured acceleration during resonant vibrations (Run 04100) with several periods of high amplitudes (right) and spectral analysis of response (left).

The total ice load calculated from model test results is scaled to full scale and compared to STRICE measurements of resonant vibrations, see Fig. 7. The peak global load is plotted against the indentation rate v/h with v being the ice drift speed and h the thickness of the ice. The agreement of forces measured in full scale and model tests indicates that the changed stiffness has no significant impact on the magnitude of ice load.

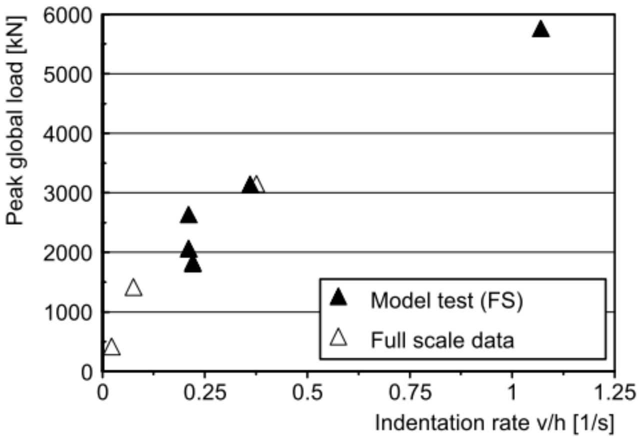

Figure 7. Peak amplitude of ice load plotted against indentation rate v/h.

Accelerations measured during model tests are not directly comparable to full scale data because of the changed stiffness. An approach is developed to convert measured values (a_1) to the response of a theoretical model with correctly scaled stiffness (a_2). Neglecting the influence of damping, the acceleration of the structure in ice plane is given by a second order ordinary differential equation (ODE), depending on actuating forces and the structure's translational stiffness:

$$a(t) = \frac{1}{k}\frac{d^2}{dt^2}(m \cdot a(t) + F_{ice}(t)) \qquad (3)$$

Assuming both $a(t)$ and $F_{ice}(t)$ being harmonic functions which oscillate with the same angular frequencyω, the ODE can be solved:

$$\hat{a} = \hat{F}\omega^2[(1 - \frac{m\omega^2}{k}) \cdot k]^{-1} \qquad (4)$$

The term $\frac{m\omega^2}{k}$ is equal for the actual and the theoretical model, because their resonance frequency is the same. Furthermore, Fig. 7 illustrates that ice loads during resonant vibrations are not or not significantly dependent on structural compliance. Hence, the acceleration is influenced by the changed stiffness only:

$$\frac{\hat{a}_1}{\hat{a}_2} = \frac{k_2}{k_1} \qquad (5)$$

This relation is applied to all IMU measurements. Fig. 8 shows good agreement of converted model test results and full scale measurements.

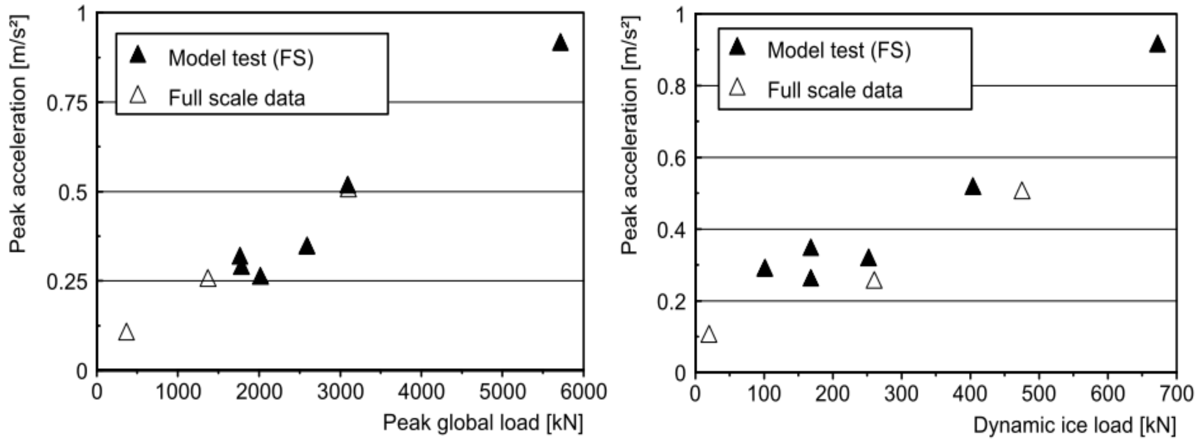

Figure 8. Peak amplitude of acceleration plotted against peak amplitude of total ice load (left) and double amplitude of the dynamic part of ice load (right).

Next to information on expected loads and response in case of ice-induced vibrations, physical model tests shall be used to identify critical velocities which may induce such vibrations. Kärnä and Turunen (1990) showed that resonant and lock-in vibrations arise when the oscillation velocity of the structure $\dot{u}$ is similar to the ice drift velocity v, with β=1 - 1.4:

$$\dot{u} = \beta v \qquad (6)$$

This relation is applicable to all resonant vibrations observed during the test campaign. As $\dot{u}$ is mainly dependent on the translational stiffness, critical velocities for differently compliant structures are divergent. Further tests on structures with correctly scaled stiffness are needed in order to verify the capability of the physical test set-up to represent critical velocities correctly.

CONCLUSION

The designed and tested physical model is capable of representing ice load and dynamic response of a cylindrical structure in case of resonant ice-induced vibrations in ice drift direction. In the present case, the changed stiffness has no significant impact on the ice load, and responses obtained during model tests converted to the correct stiffness are similar to full scale measurements. As these events are strongly affected by dynamic ice-structure interaction, this agreement indicates a correct representation of basic interaction mechanisms at model scale.

The number of comparable events is small since a lot of observed vibrations have been influenced by the compliant y-direction. This problem has to be overcome in future tests.

However, the most severe vibrations observed in model tests follow the direction of ice load and are not influenced by the flexibility in y-direction, confirming the conclusions drawn from full scale data analysis.
More tests with a correctly scaled structure are needed to investigate the dependence of critical velocities on the structural compliance and the model's capability of representing them. The physical test set-up is a good approach to investigate dynamic ice-structure interaction at model scale and will be optimized and extended for future applications.

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