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TESTS ON DYNAMIC ICE-STRUCTURE INTERACION

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ABSTRACT

This paper addresses the problem of ice induced vibration of offshore structures. Compliant structures having vertical ice walls may suffer from very severe vibrations. Several theories have been proposed to predict these vibrations. However, physical details of this phenomenon are not fully understood. Conical structures are deemed to be less sensitive to vibrations. Recent full-scale measurements made in the Bohai Bay indicate that also these structures my experience excessive vibrations caused by ice.

Indentation tests were done at the ARCTEC laboratory at the Hamburg Ship Model Basin, Hamburg to clarify details of ice induced vibration. Sheets of columnar grained saline ice was used in the tests. The parameters that were varied included the structure's compliance and damping, indentation velocity and the structural geometry at the water line. The paper provides tests results that were obtained using vertical and conical model structures.

INTRODUCTION

Ice-induced vibrations of compliant marine structures have been studied on several occasions since Peyton (1966) published his experimental results. Phenomenological and numerical models are available to analyze this phenomenon. However, details of the ice-structure interaction process that lead to this phenomenon is not properly understood. Ice-induced vibrations may occur on several kinds of structures. These include offhore structures for hydrocarbon production and aids of navigation. Designers will face the same problem in the future while constructing offshore wind power generators for the ice covered areas of the Baltic Sea. Therefore, there is now an urgent need to understand better the physical phenomena involved in ice-induced vibrations.

Ice-induced vibrations that occur on vertical structures have been characterized in the past using either the concepts of resonant vibration or self-induced vibration. The latter is known also as a lock-in phenomenon. Installing a cone at the ice level is one of the methods to reduce the quasi-static global ice force and the ice induced vibrations. However, recent full-scale data from the Bohai Bay (Yue and Bi, 2000) show that vibrations on conical structures can be excessive. It is anticipated that a similar situation may arise on offshore wind power generators.

This paper describes a series of ice laboratory tests that were made to clarify details of the dynamic ice-structure interaction. Special efforts were made to study how the strutural stiffness, damping and the displacement at the ice level influence the interaction.

EXPERIMENTAL SETUP

The tests were made in the Large Ice Basin of the Hamburg Ship Model Basin (HSVA). This ice basin is 78 m long and 10 m wide. A motor-driven carriage of the basin provides a maximum towing force of 50 kN.

Two stiff and heavy vertical columns were fixed on the carriage. The test structure was installed on these columns as illustrated in Fig. 1. The structure was a cross-type, welded steel structure. The vertical and horizontal beams of the test structure were fabricated from rectangular hollow sections. The vertical column was connected to the horizontal torsion beam that provided compliance for the structure. The ends of the torsion beam were connected to the carriage columns A and B.

One of the aims of this test series was to use a test structure that has more than just one natural mode that is relevant for the structural response. Therefore, different concepts were used to tune the structure's dynamic behavior. First, the test structure had an option to have rubber springs in the connections between the columns A and B and the horizontal beam. Second, three additional masses were used to tune the dynamic properties of the test structure. Two of them were attached at the upper part of the vertical beam as shown in Figs. 1 and 2. The third mass was inside the vertical beam, at its lower end. Additional tensile elements were used to prevent excessive local deformations of the structure. A finite element model (Fig. 3) was used in the initial design phase to find appropriate dimension for the test structure

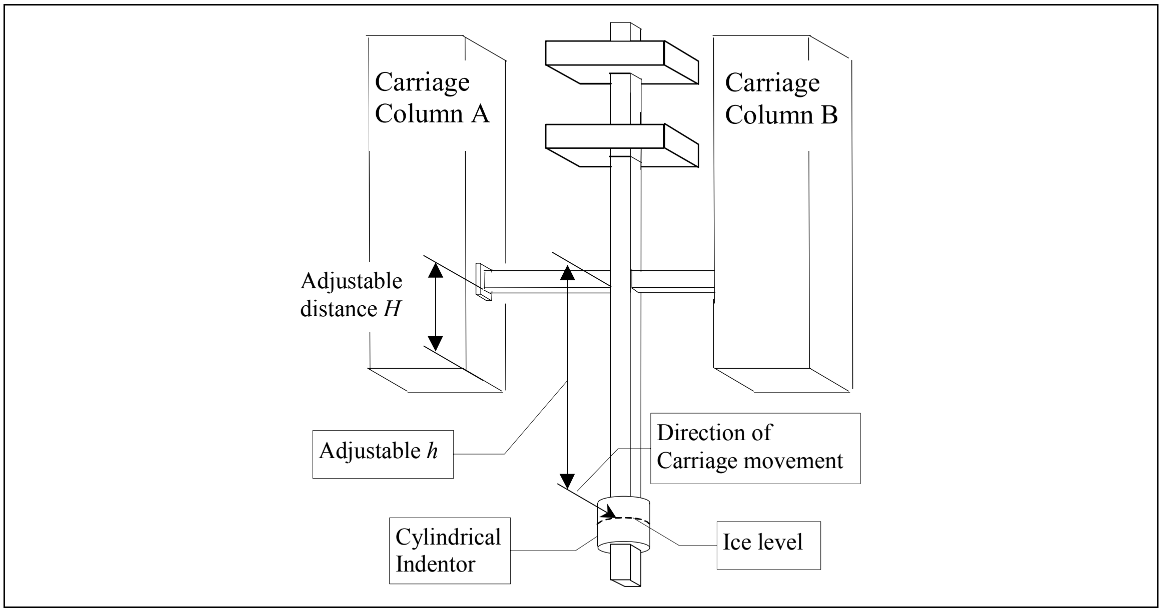

Figure 1. Sketch of the test structure and it's connection to the HSVA's Carriage.

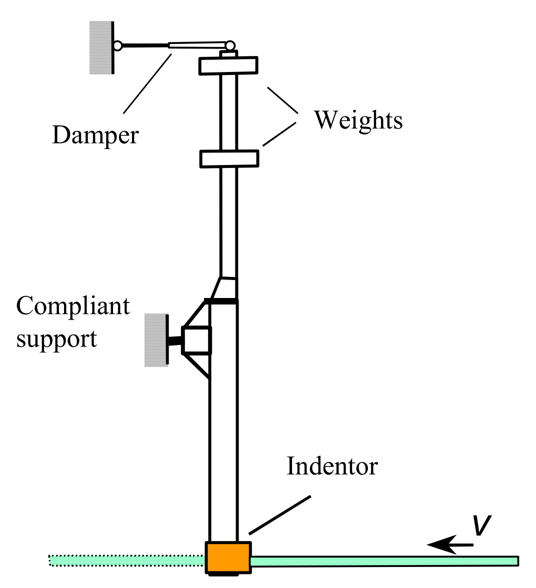

Figure 2. Interaction between the test structure and the ice.

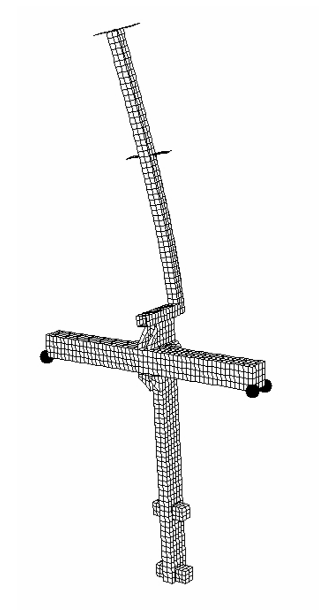

Figure 3. Eigenmodes and eigenfrequencies were studied using a FEM model

Structural variants

The stiffness of the structure "as seen by the ice" was varied during the test series by changing the distance of structure (*H)* and the position of the indentor (*h*) as shown in Fig. 1. Additional changes in the stiffness properties were achieved by modifying the joints between the horizontal beam and the columns A and B. The stiffness and eigenfrequences were verified experimentally after each major change of the structural properties.

A frictional damper with a variable damping capacity was used in some of the tests. The damper was connected between the top of the structure and the carriage (Fig. 2). The damping forces were measured by a load cell. Two spring loaded screws were used to adjust the damping force.

Measurements and observations

Ice force measurements were done indirectly. Three sets of strain gauges were used to obtain three independent signals for the forces. One set of strain gauges was located in the horizontal beam to measure the torsional moment. Two sets of strain gauges were fixed on the vertical beam to measure the shear force and bending moment. Damping forces were measured, when the friction damper was active.

Two displacement transducers and several accelerometers were used to record the dynamic state of structural displacements. The position and speed of the main carriage were also measured in each test.

All the tests were recorded using video cameras and digital cameras. One conventional camera was attached to the carriage beam above indentor so that the indentor behavior and ice failure could be recorded simultaneously. Freehand digital video and still cameras were used also. Compressed air was used to blow crushed ice away in front of the indentor as shown in Fig. 4(a).

Indentors

Two different types of indentors were used in the tests. Most tests were done using a cylindrical indentor having a diameter of 114 mm. (Fig. 4(a)). A faceted cone with a waterline deameter of 220 mm was also used in a few tests (Fig. 4(b)). Compared to full scale structrues, the geometric scale was in the range from 1/50 to 1/200. The angle of inclination was 30 degrees for the conical indentor. The indentors were fixed to the vertical beam using bolts so that the position of the indentor could be adjusted (*h* in Fig. 1).

(a) (b)

Figure 4. (a) Test set-up with a cylindrical indentor and an air blow system. (b) Conical indentor after the tests.

Model ice

The tests were done using columnar grained model ice. The ice was prepared using a conventional method where a pre-cooled water having a salinity of 9 ppt was seeded to initiate the growing process of the ice. The salinity of the ice varied from 2.4 ppt to 4.6 ppt. The compressive strength varied within the ice sheets from 0.3 MPa to 0.7 Mpa coresponding to the salinity content. The specimen temperature varied from -3 °C to -5 °C during the compression tests. Most of the tests were done at an air temperature of -15 °C. The ice thickness varied in different ice sheets from 80 mm to 90 mm.

TEST RESULTS

Tests were done by pushing the structure against a uniform ice sheet that was laterally confined between the walls of the ice basin. Five different variants of the basic test structure and three different ice sheets were used. Figures 5 to 7 show results obtained with the test structure SV8 having the two lowest natural frequencies at 6.7 Hz and 17.2 Hz. The corresponding damping ratios as a fraction of critical were 0.7% and 2%.

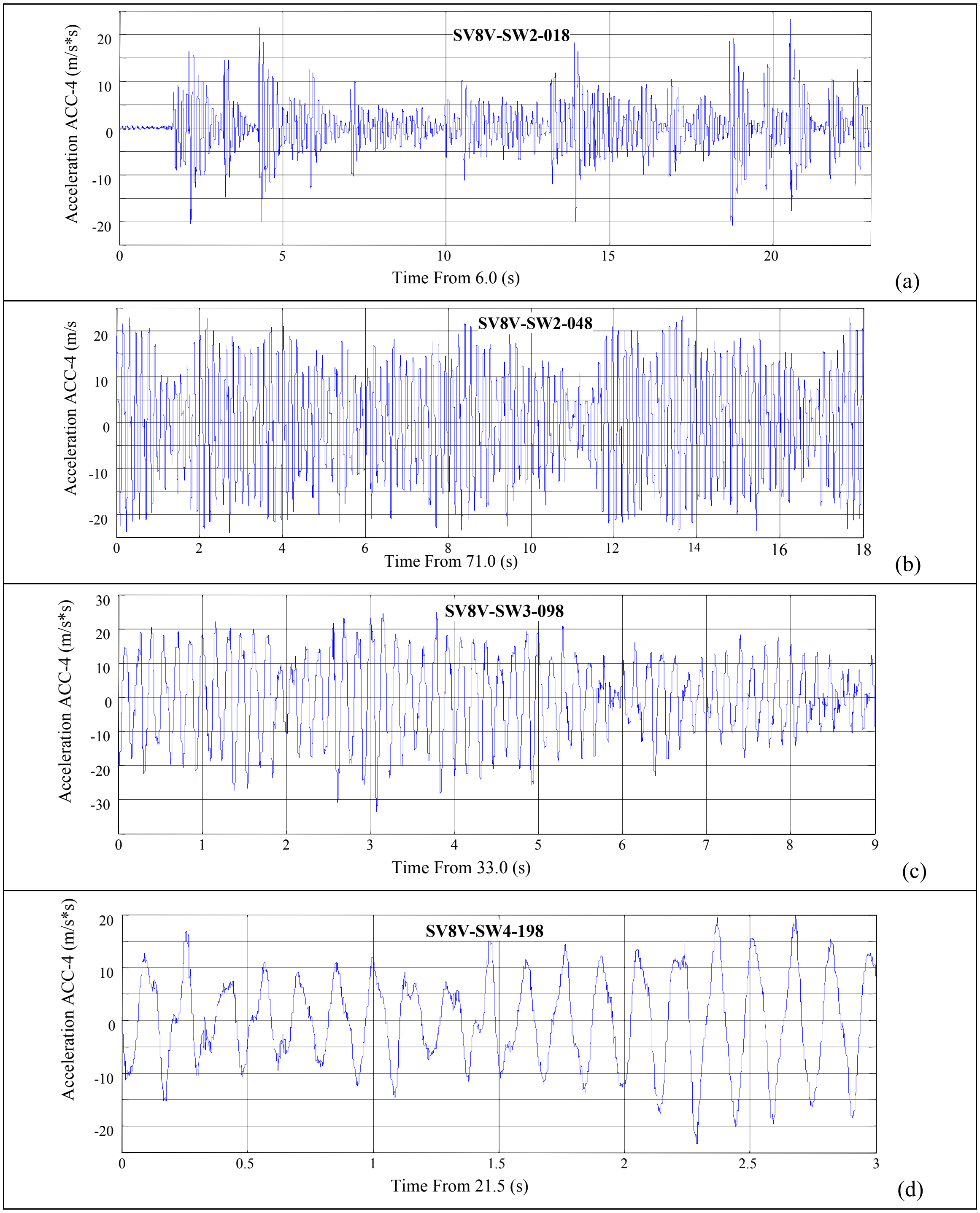

Figure 5. Measured accelerations at the top of the structure at different indentation velocities. The cylindrical indentor was used. (a) v = 18 mm/s, (b) v = 48 mm/s, (c) v = 98 mm/s, (d) v = 198 mm/s.

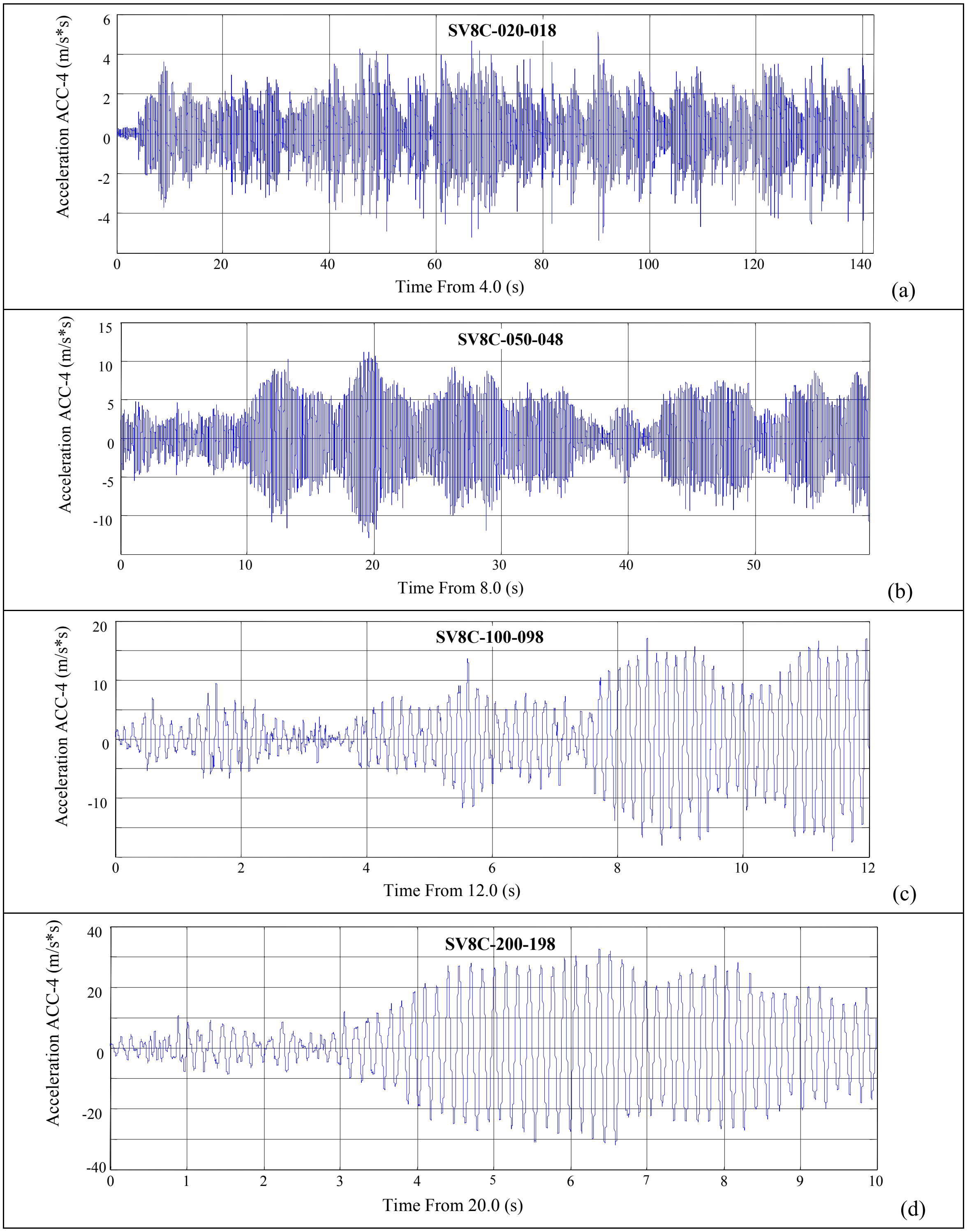

Figure 6. Measured accelerations at the top of the structure at different indentation velocities. The faceted cone was used as the indentor. (a) v = 18 mm/s, (b) v = 48 mm/s, (c) v = 98 mm/s, (d) v = 198 mm/s.

Figure 5 shows results in conditions where a cylindrical indentor was used. The changes of the structural response are shown as the indentation velocity increased from about 20 mm/s to 200 mm/s. At the low velocities the waterline stiffness of the structure appears to be the main controlling parameter of the interaction. As the ice velocity is low, the structure follows the displacement of the ice edge until the ice fails. The accelerations of the structure are small during this loading phase. A phase of transient vibrations is triggered by the ice failure. These transients can be seen in Fig. 5(a).

The inertia forces of the structure start to control the interaction as the indentation velocity increases. Steady state vibration may occur, in particular if the structural damping is low. This test structure experienced the highest response at the velocities of 100 mm/s to 120 mm/s (Figs. 5(c) and 7). At very high velocities the response is reduced and changes from a narrow band response to broad band response.

Figure 6 shows the response of the test structure SV8 in conditions where the faceted cone was used as the indentor. Comparisons with Fig. 5 show that the cone reduced the response when the indentation velocity was smaller than about 180 mm/s (see also Fig. 7). A resonant condition was found at indentation velocity was 200 mm/s. This was caused by the particular ice failure mode that prevailed at all ice velocities while the cone was used. The grain boundaries of the columnar grained ice were weak. Therefore, the ice did not fail by a bending failure mode that is common for conical structures. Instead, sequential shear failures occurred along the grain boundaries due to the vertical load component created by the cone. The ice failure length varied between 30 mm and 40 mm for the 90 mm thick ice sheet. Therefore the ice failure process created a narrow band periodical force.

Figure 7 shows a comparison between the measured response in the two cases where a cylinder and a faceted cone were used as indentors. It is commonly deemed that the dynamic response is reduced significantly when the waterline geometry of the structure is inclined instead of vertical. In this test series the cone reduced the maximum response. However, the reduction was only small.

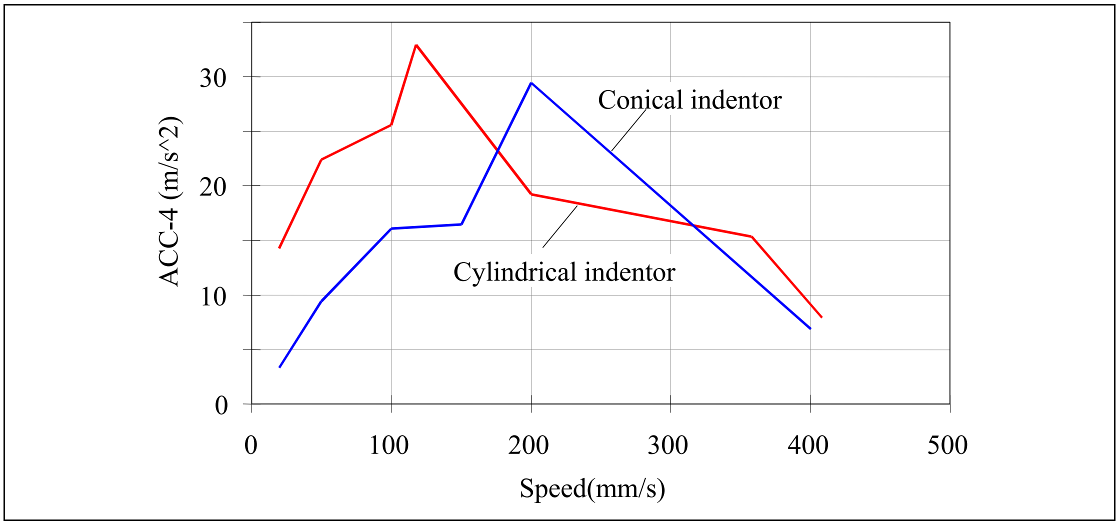

Figure 7. Peak acceleration at the top of the test structure SV8 as a function of indentation velocity.

CONCLUSIONS

A series of indentation tests was done using saline columnar grained ice. The dynamic properties of the test structure were varied during the test series. In particular the stiffness of the structure "as seen by the ice" was varied as well as the structural damping. All details of the test programme are described by Kärnä et al. (2003). The present paper shows selected results for a structure that had a low structural damping. Steady state vibrations occurred at the lowest natural frequency at some ice velocities when a cylinder was used as an indentor. Heavy vibrations were found also when a faceted cone was used as the indentor. These vibrations were caused by a resonant condition that occurred due to a specific ice failure mode.

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