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Influence of pitch motion on level ice actions

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ABSTRACT

The effect of pitch motion on the forces applied to conical structures by ice has been analysed by means of model tests and numerical analyses. The model test setup allowed a direct comparison between a cone in fixed condition and compliant condition in which it was able to rotate only in pitch. A numerical analysis was performed to demonstrate results and conclusions from the model tests.

It was determined that the structural response (pitch motion) affected the loading process and the ice forces. The model test demonstrated that compared to the fixed cone, the compliant cone exhibited a reduction in the measured ice forces caused by drifting level ice. The numerical analyses supported the findings of the model test campaign. Several loading conditions were investigated by changing the ice drift velocities. Both the structural response and the loading process of the compliant cone changed under different ice drift velocities due to different dynamic response behaviours. It was concluded that the pitch rotation significantly influenced the ice forces acting on the cone, illustrating the importance of including structural response in the design of Arctic structures when calculating ice actions.

1. Introduction

Station-kept floating structures are attractive for performance of marine operations in Arctic areas, where developments move towards deeper waters. When these structures encounter drifting ice features, the ice features exert a force on the structures. The floater's response is based on its ability to resist the ice actions and force levels until the ice feature eventually fails. The interaction process between a floating structure and drifting ice is complex because the structure may influence the loading process and failure mode of the ice. The process is nonlinear, and it is neither well explained nor well understood.

In recent years, several model test campaigns have been conducted on various moored structures exposed to drifting ice, and the observed motions of these structures have been discussed (e.g., Aksnes, 2010a; Bruun et al., 2009; Dalane et al., 2008, 2009; Ettema and Nixon, 2005; Murray et al., 2009). Both model test campaigns and full-scale measurements have frequently studied the mooring line forces (e.g., Comfort et al., 1999; Jensen et al., 2008; Løset et al., 1998; Toyama and Yashima, 1985; Wright, 1999), but the excitation forces created by the ice features are seldom recorded, as they are difficult to measure. When ice excitation forces are given, they have generally been based on back-calculated forces via equations of dynamic equilibrium (Dalane et al., 2008; Karulin et al., 2004; Lundamo et al., 2008; Murray et al., 2009). Back calculations can be an efficient means of extracting ice actions from an experiment when all dynamic parameters in the calculation are known. However, because a structure's response is dependent on its specific dynamic parameters, i.e., mass, damping terms and stiffnesses that are specific to each independent floater, it may be difficult to compare different floaters' back-calculated forces due to the influence of each floater's response. The complexity of the ice loading process and the limitations of the model test measurement have made it difficult to quantify specific response effects on ice action.

To develop a better understanding of the subject and develop more accurate numerical models, various studies have focused on different motions and the effects on measured forces. Frederking and Schwarz (1982) performed a model test campaign in which a cone was forced to oscillate at given frequencies in a vertical direction only or in a circular motion (combined horizontal and vertical direction), observing that the force level changed in response to the oscillatory frequency. Matsuishi and Ettema (1985) found that a conical platform experienced greater ice force when it was restrained compared to when it was free to pitch and heave for relatively slow speeds of interaction. Mróz et al. (2008) introduced the concept of using a compliant rotating cone to mitigate dynamic ice actions on offshore windmills and illustrated this effect through numerical studies. Aksnes (2010a, 2011) constructed a model test campaign with the purpose of investigating the horizontal stiffness effect on moored vessels, observing varying responses and mooring forces at different ice drift velocities and mooring stiffnesses.

To further document the effect of a floater experiencing a specific significant motion, this study has designed a model test campaign and numerical model to investigate the effect of pitch motion on ice actions. The purpose of the model test was fundamental research on an important topic for engineers and designers, and the test setup was optimised for the direct comparison of the model test's results. Level ice actions were examined to ensure that similar test conditions were present in all the model test runs that analysed different drift velocities. A

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downward-facing cone was chosen for use as the structure in this study because its characteristic shape is relevant to that of Arctic floaters, directly linked to symmetric floaters (i.e., Kulluk), and closely linked to the bow of an icebreaker. The cone model was tested in two configurations-completely fixed or able to rotate only in pitch-and exposed to four different ice drift velocities. By simplifying the model test to either be fixed or to have only one degree of freedom, one can capture the response effect on the ice-structure interaction. The model test results are supported by independent results from a developed numerical model based on principles in ISO 19906 (2010) and modified for a dynamic time-domain simulation. The main focus of this paper is qualitative observations regarding pitch motion effects on ice actions depending on ice drift velocity.

This paper begins by describing the experimental model test setup, which is followed by a description of the results. The numerical study is then explained, followed by the results obtained through the numerical simulations. Finally, conclusions and a discussion that synthesises the results of the model test and numerical study are provided.

2. Test setup

The model test was conducted in April 2009 at the Hamburg Ship Model Basin (HSVA) in Germany. The ice tank at HSVA is 78 m long, 10 m wide and 2.5 m deep. All values presented in this text represent model test values.

The tested model was a hollow conical frustum made of thick steel (Fig. 1) with a diameter D of 1325 mm, a draft of 568 mm and an inclination angle to the waterline ϕ of 61.4°. Its structural dimensions are summarised in Table 1 and Fig. 2. The bottom of the model was open so that water could float freely inside the model. Styrofoam was placed inside the frustum to increase the buoyancy forces and, therefore, the stiffness of the system. The Styrofoam was submerged at all times. The model was connected to the driving carriage in the tank through a connection system consisting of beams, a system of load cells and a rotational hinge(Fig. 1). The load cell system consisted of three triaxial load cells arranged in a triangular configuration between two solid steel plates. The top steel plate was connected to the beam attached to the carriage, while the bottom plate was connected to a stiff frame attached to the rotational hinge. The rotational hinge gave the cone a rotational degree of freedom. In this paper, the measured rotation is referred to as the pitch angle and denoted by η; it corresponds to the rotational degree of freedom around the y axis in the body fixed coordinate system x, y, z. The body fixed right-handed coordinate system x, y, z is fixed such that the y-axis goes through the centre of the rotational hinge, the x-axis is parallel to the ice drift direction, and the z-axis is defined positive upwards (Fig. 2).

Table 1
Main dimensions of the tested model.

Parameter	Value
Waterline diameter D [mm]	1325
Draught [mm]	568
Cone height [mm]	908
Cone angle ψ [°]	28.6
Waterline inclination ϕ [°]	61.4
Waterline to rotation point [mm]	522
Friction coefficient	0.1
Natural frequency fixed mode [Hz]	7.3
Pitch natural period [s]	3.7
Pitch damping ratio [−]	0.1
Pitch stiffness k [Nm/rad]	660
Mass moment of inertia [kgm^2]	225

The test setup allowed the model to be tested in fixed and compliant conditions. In fixed mode, four stiff beams (two on each side) were mounted a distance from the rotational hinge between the cone and a frame under the load cell system, preventing its rotation. In compliant mode, the stiff beams were replaced with springs. The springs were mounted with pretension to provide a linear stiffness for all the elevations obtained in the tests. One spring was used on each side of the rotational hinge. Fig. 1 illustrates the use of these beams and springs at the same time.

The triaxial load cells were used to report global ice forces on the cone. They were placed above the rotational hinge and were, therefore, independent of whether the testing mode was fixed or compliant. The load cells measured forces in three directions as well as three moments. An inclinometer was placed on the cone's port side at $x = 0$. The inclinometer reported the inclination angle η in the compliant mode tests. All the data sensors had a sampling frequency of 100 Hz.

The properties of the system was determined by tests performed in open water, as given in Table 1. Hammer impacts on the model were used to determine the natural period of the stiff model. The compliant model was loaded using weights to determine the rotational stiffness. The (damped) natural period and the damping coefficient in pitch were calculated from decay tests, and the corresponding rotational mass moment of inertia was calculated based on the measured parameters. Open water towing tests exerted only small forces over the entire tested velocity range compared to the forces experienced in the level ice tests and were, therefore, neglected. The entire model setup was connected to the driving carriage, and during some of the test runs, vibrations from the driving carriage created noise in the force signal. The force signals were, therefore, filtered using a low pass filter with a

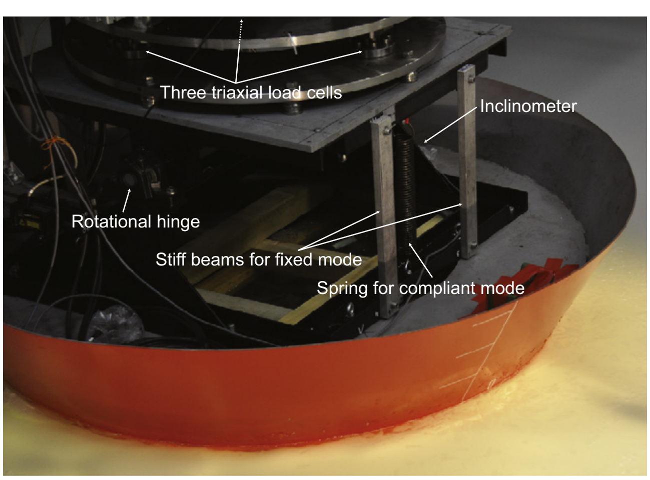

Fig. 1. Picture of the test setup, illustrating the model constrained by both the fixing beams used in fixed mode and the springs used in compliant mode. The setup of the springs and beam are similar in the back.

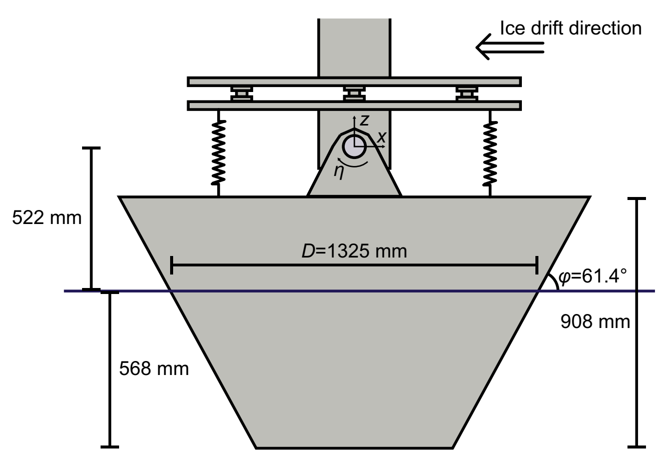

Fig. 2. Main dimensions of the cone used in the model test.