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Experimental and numerical investigation of wave induced forces and motions of partially submerged bodies near a fixed structure in irregular waves

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ABSTRACT

This paper is the third of a series covering investigations of the wave induced force and motion behavior of ice masses near a fixed structure. The objective of this phase of the study was to determine whether the effects observed in regular waves (Sayeed et al. (2017b, 2018)) still held in irregular seas. In the present case, wave characteristics measured in front of the fixed structure showed that the significant wave heights follow a standing wave pattern generated by the superposition of the incident and reflected peak frequency wave. Thus it may be inferred that the significant surge and heave forces and motions will be increased or decreased at the node and antinode locations in front of the structure as previously observed for regular waves. Force spectra generated from regular wave force data (Sayeed et al. 2017b) and wave measurements from the present study showed that beyond the nodal location at $\frac{D}{\lambda_p} = 0.25$, the significant surge force goes down and significant heave force goes up as the body gets close to the structure. Direct measurements of irregular wave forces on a fixed berg model at different proximity to the fixed structure demonstrate the change in significant wave forces based on the ratio of separation distance to peak wavelength. When the berg body is positioned closer to the fixed structure, the normalized significant forces in the horizontal direction decrease, and the normalized significant forces in the vertical direction increase. Significant differences were found between the directly measured force spectra and those produced by linear superposition of regular wave force transfer functions. This is attributed to non-linear effects arising from the iceberg profile and low freeboard.

Free floating motion experiments showed smaller differences in the surge and heave velocity spectra due to the presence of the structure. This is because there is insufficient motion data at any specific location to capture the motion responses for all the frequencies in the spectrum. The proximity effect on wave loads and wave induced motions in the vertical direction is found to be more pronounced than the same in the horizontal direction.

Numerical simulations using RANS based commercial CFD code Flow3D© are compared to the experimental results. Selected test cases from both force and motion experiments are simulated in irregular waves generated from selected experimental wave spectra. Numerical results for irregular waves demonstrate the ability to simulate random waves and resulting forces and motions with trends comparable to the experimental results.

1. Introduction

Fixed and floating offshore structures in Arctic and sub-arctic regions face unique challenge in their structural design because of the unique environmental loading by various glacial ice fragments. Fixed structures are designed to withstand large iceberg impacts, whereas floating structures can avoid interaction with large icebergs by moving off location. Wave driven small (1,000t – 20,000t) pieces of glacial ice, bergy bit or growler are a potential hazard for offshore installations operating in ice infested waters. Smaller ice masses are also harder to detect in bad weather, at night, or in heavy seas. The wave induced motion of smaller ice masses can substantially exceed their mean drift speed (Attwood (1987)).

Estimation of impact load arising from wave driven ice masses with offshore structures is heavily dependent on the input collision energy and collision energy is largely dependent on the final velocity prior to

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impact. The close proximity hydrodynamic interaction between an iceberg or a bergy bit and an offshore structure is an important factor that influences the impact velocity. Sayeed et al. (2017a) conducted a comprehensive review to identify the significance of hydrodynamic interaction of ice masses in close proximity with arctic offshore structures just prior to impact and also to identify related research gaps in this area. A potential research gap exists in the study of the viscosity dominated, very near field region, where several complicated phenomena such as negative wave drift force (against the direction of propagation of the waves), fluid cushioning, wave shadowing, reduction in impact velocity, change in added mass, hydrodynamic damping, eccentric impact etc. Have been observed in several physical model test programs. These effects are more obvious for less transparent fixed or floating offshore structures such as Gravity Base Structures or large ship-shaped Production Platforms and for smaller ice masses and bergy bits. Change in impact velocity could conceivably change the failure mode of ice (ductile, transition or brittle) thus changing the effective pressure. Ignoring these effects may result in an overestimation in impact load which will ultimately affect the design and cost of the structure.

A considerable volume of experimental work has been directed towards the iceberg-structure interaction problem. Attwood (1987), and Lever et al. (1988a, 1988b) carried out a series of experiments and found that small icebergs behaved like a fluid particle for wave length/iceberg size ratios greater than 13. Salvalaggio and Rojansky (1986) observed that no impact occurred if the iceberg diameter was less than approximately half the structure diameter. Lever et al. (1990a) extended their impact velocity probability statistics to include a number of different iceberg shapes. Lever et al. (1990b) conducted model tests of wave driven bergy bits impacting with a semi-submersible in irregular waves. Mak et al. (1990) conducted a similar study in regular and irregular waves with a floating oil production platform with larger physical dimensions than the transparent semi-submersible tested by Lever et al. (1990b). Open water significant velocities were found to be 10–40% higher than significant impact velocities.

McTaggart (1989), and Isaacson and McTaggart (1990a, 1990c) investigated the hydrodynamic forces during iceberg drift in proximity with an offshore structure through model tests and numerical analysis. For the waves-only condition, no impact occurred when the ratio of iceberg diameter and structure diameter is less than, or equal to, 0.2 whereas Salvalaggio and Rojansky (1986) in their experiments found the ratio to be 0.5. It was reported that the presence of the structure can result in 10% or more velocity reduction for smaller icebergs (iceberg-structure diameter ratio less than 0.2) approaching the structure.

Model experiments of the Terra Nova FPSO in collision with an iceberg (100,000t) and a bergy bit (3,600t) conducted by Colbourne et al. (1998) revealed that impact energies may be reduced for the smaller bergs in higher sea states and it was speculated that the radiated waves in very near field region results in confused collision trends. Colbourne (2000) indicated that increased input wave energy did not lead to increasing impact energy for small ice pieces and postulated that the effect may be due to reflection of waves where the reflected wave energy reduced the berg velocity.

Klopman and van der Meer (1999) investigated the spatial variation of wave spectrum and significant wave height in front of a vertical wall and a rubble mound breakwater in random waves. The significant wave heights show a standing wave pattern extending over two times the peak wavelength for the given JONSWAP spectrum. The findings of nodal and antinodal frequencies follow the patterns of linear wave theory.

Gagnon (2004) conducted physical model tests to investigate the hydrodynamic interaction between a floating ice mass and a tanker passing at speed. This study indicated that the radiation/proximity effect, arising from radiated waves and underwater pressure generated by the passing hull, can be significant but this work did not directly consider collisions. An increase in maximum sway motion of the ice mass was also observed and the author attributed this to negative added mass and drift force because of standing waves between the tanker and the ice mass. Tsarau et al. (2014) towed a cylinder (structure) past a fixed submerged sphere (ice mass) at different speeds and separation distances in calm water. The associated hydrodynamic forces varied between positive and negative depending on the separation distance between the cylinder and the sphere. Kim (2014) conducted drop tests of laboratory grown ice blocks onto stiffened steel panels in air and impact tests in water with a moored structure and ice blocks towed at two different speeds. The objective was to investigate simultaneous inelastic deformations of ice and steel structure and the drop tests in air helped to separate associated hydrodynamic aspects.

McGovern and Bai (2014a) conducted model tests to investigate the kinematics of isolated ice floes of different sizes and shapes in regular waves. The motions observed for ice floes were found to be different than those of icebergs because of flat low draft geometry of ice floes. At wavelength to characteristic length ratio of 3.3–5, the floe behaved like a fluid particle. McGovern and Bai (2014b) also investigated the presence of a circular cylinder on the kinematics of ice floes in regular and irregular waves. At separation distance to cylinder diameter ratio less than 10, increase in heave response and significant reduction in surge response was observed. The mean drift velocities also showed low and negative values as the ice floe approached head-on towards the cylinder.

Sayeed et al. (2017b) measured the wave loads on different sized spherical ice masses at different proximity to a fixed structure using a six component dynamometer. The experimental results showed that the separation distance to wavelength ratio dictates the corresponding wave loads in surge and heave directions. The mean drift force in the horizontal direction becomes negative (against the direction of wave propagation) for most of the cases when the body is close to the structure. Also, as the body is positioned closer to the structure, the non-dimensional RMS forces in the horizontal direction decrease and the non-dimensional RMS forces in the vertical direction increase. Sayeed et al. (2018) measured the wave induced motions of different sized free floating ice masses approaching a fixed structure. The experimental results of motion data showed excellent correlation with the force data gathered in the first phase (Sayeed et al. (2017b). Similar to previous studies, the separation distance to wavelength ratio is shown to dictate the corresponding wave induced motions. The motions are increased or decreased at nodes and antinodes of the standing wave in front of the structure. At nodes the surge motions are increased and heave motions are decreased and at antinodes the surge motions are decreased and heave motions are increased. As the body gets close to the structure, the surge motion slows and at the same time the heave motion is increased.

Most of the numerical studies that have been used to model the near field hydrodynamic interaction problem have utilized potential flow theory which assumes inviscid and irrotational flow. Isaacson and Stritto (1986) developed a diffraction theory model with oscillatory and drift motions to investigate the two body interaction problem. Cheung (1987) and Isaacson and Cheung (1988a, 1988b) used their potential flow code and observed an increase in added mass as separation distance decreased. Lever and Sen (1987) utilized linear potential flow theory developed by Sen (1983) to conduct risk analysis of iceberg impact considering wave-induced motions into account. Lever et al. (1988a) and Attwood (1987) validated the results from linear potential theory using wave-induced motion data from wave tank experiments.

Various hydrodynamic aspects such as added mass, wave induced oscillatory motion, and modification of iceberg motion due to the presence of a structure during iceberg impact are investigated by McTaggart (1989) using a potential flow numerical model. Isaacson and McTaggart (1990a, 1990b) conducted experiments to investigate iceberg drift in proximity with offshore structures and compared the results with a potential flow based numerical model. For the current-only cases, agreement was reasonable for velocity ratios but the numerical