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Hydrodynamic responses of a thin floating disk to regular waves

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ABSTRACT

The surge, heave and pitch motions of two solitary, thin, floating disks, extracted from laboratory wave basin experiments are presented. The motions are forced by regular incident waves, for a range of wave amplitudes and frequencies. One disk has a barrier attached to its edge to stop the incident waves from washing across its upper surface. It is shown that the motions of the disk without the barrier are smaller than those of the disk with the barrier. Moreover, it is shown that the amplitudes of the motions, relative to the incident amplitude, decrease with increasing incident wave amplitude for the disk without a barrier and for short incident wavelengths. Two theoretical models of the disk motions are considered. One is based on slope-sliding theory and the other on combined linear potential-flow and thin-plate theories. The models are shown to have almost the same form in the long-wavelength regime. The potential-flow/thin-plate model is shown to capture the experimentally measured disk motions with reasonable accuracy.

1. Introduction

As ocean surface waves progress deeper into the partially sea ice covered ocean, they encounter discrete, relatively thin chunks of ice (floes) of increasing horizontal dimensions (Squire and Moore, 1980). The range of dimensions depends on the geographic location and season. However, the floe diameters can be as small as a metre, in the case of pancake ice, and up to hundreds of metres. The waves are attenuated by their interactions with the floes before they reach the quasi-continuous ice pack (Shen and Ackley, 1991), notwithstanding the large floes pushed into the outer fringes of the ice cover by random ice motions, which are subsequently broken up by the waves (Squire et al., 1995). The region of the ice-covered ocean in which wave activity remains significant is known as the marginal ice zone (MIZ).

Waves impact the ice cover in the MIZ. They break up the ice into smaller floes (Prinsenberg and Peterson, 2011), which are more prone to melting and easily stirred up by winds, currents and waves. For example, waves herd the floes into groups (Wadhams, 1983). Further, waves cause floes to collide with one another (Martin and Becker, 1987), which cause them to erode and produce rubble (McKenna and Croker, 1990). Collisions sometimes turn into rafting events, and if the floes stay in contact they bond (Dai et al., 2004). Waves also introduce warm water and overwash the floes, which accelerates melt (Wadhams et al., 1979; Massom and Stammerjohn, 2010).

Arctic sea ice is retreating polewards, particularly following the summer melt season (Stroeve et al., 2014). Strong and Rigor (2013) use satellite data from 1979 to 2011 to show that, in addition to the poleward shift of the Arctic ice cover, the width of the MIZ is increasing by approximately 13 km per decade during the summer months. (They defined the MIZ based on the ice covering 15–80 % of the ocean surface.) Thomson and Rogers (2014), amongst others, use models and data to show that winds generate large-amplitude waves in the areas of open water left by the ice retreat. Squire (2011), for example, argues that these stronger waves are contributing to the expansion of the MIZ, thus further weakening the ice cover, accelerating ice retreat and promoting even stronger waves.

Theoretical/numerical models have been developed to predict wave impacts on the ice cover. Shen and Ackley (1991) used a one-dimensional model to study collisions between floes and herding. They used the slope-sliding model of Rumer et al. (1979) to calculate the horizontal motions of the floes induced by waves. The slope-sliding model is an extension of Morison's equation, which includes a force due to the slope of the wave field. The model is derived on the assumption that floes do not modify the wave field, i.e. the floe diameter is much less than the wavelength. It predicts the horizontal motion of a floe to be the sum of an oscillatory surge motion at the period of the incident wave, and a steady drift in the direction of the incident wave. Shen and Zhong (2001) derived analytical solutions to the slope-sliding model in certain cases. Marchenko (1999)

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independently derived a similar slope-sliding theory to Rumer et al. (1979). Grotmaack and Meylan (2006) related the two theories and identified an error in the derivation of Rumer et al. (1979), although they noted Marchenko (1999) neglected the floe's added mass.

Kohout and Meylan (2008) and Williams et al. (2013a, 2013b) modelled wave-induced breakup of a large group of ice floes, and applied breakup criteria that extended the earlier work of Langhorne et al. (2001). The kernel of both models is a model of a wave interacting with a solitary floe. The wave–floe interaction model uses linear potential-flow theory to model water motions and thin-plate theory to model the floe. The linear potential-flow/thin-plate model is commonly used to study wave–floe interactions (see the review of Squire, 2007, for example).

Kohout and Meylan (2008) and Williams et al. (2013a, 2013b) used two-dimensional models (one horizontal dimension and one depth dimension). Masson and LeBlond (1989), Meylan et al. (1997) and Bennetts et al. (2010) developed three-dimensional models of waves propagating through large groups of floes. They focussed on the attenuation of wave energy into the ice-covered ocean and did not model breakup or any other impact of the waves on the ice cover. Masson and LeBlond (1989) and Meylan et al. (1997) modelled the floes using the thin-disk models of Isaacson (1982) and Meylan and Squire (1996), respectively, noting the former is a rigid model and the latter is an elastic model. Bennetts et al. (2010) used a disk model and also a square-plate model, using the finite-element approach of Meylan (2002), but found the different shapes did not significantly alter the predicted attenuation rates.

A handful of laboratory experimental studies have been conducted recently to assess the accuracy of the theoretical models, and indicate phenomena the models do not capture. The experiments focus on the ability of the models to predict interactions between water waves and thin floating plates.

Bennetts and Williams (2015) used laboratory wave basin experiments to validate the model of Meylan et al. (1997), and the two-dimensional model of Bennetts and Squire (2012), which was used by Williams et al. (2013a, 2013b). They used arrays of 40–80 identical wooden disks to model the ice cover, and measured the proportion of wave energy it transmitted for regular incident waves over a range of wave frequencies and, in two cases, for two different amplitudes. The quotient of thickness, H, over diameter, D, for the disks was $H/D \approx 3.3 \times 10^{-2}$. The quotient of the incident wavelength, λ, over the disk diameters was in the range $\lambda/D \approx 0.67$–6.28. The incident steepness, represented by the product ka, where $k = 2\pi/\lambda$ is the wavenumber and a is the incident amplitude, was in the range $ka \approx 0.04$–0.26. They showed the models predict the transmitted energy accurately for small incident amplitudes and low concentrations of the disks. They observed the models were inaccurate for the larger incident amplitudes when wave overwash of the disks was strong—overwash is a form of green water that refers to the wave running semi-continuously over the top of the disks, due to their small freeboards. Further, they provided evidence to show the models were inaccurate for high concentrations due to collisions between the disks, caused by out of phase surge motion of adjacent disks, and rafting, caused by out of phase heave and pitch motions. The potential-flow/thin-plate model does not include the highly nonlinear processes of overwash and collisions.

Modelling collisions between disks requires an accurate model of the surge motion of a solitary disk. Heave and pitch motions must also be modelled to predict rafting. However, the potential-flow/thin-plate and slope-sliding models' predictions of these oscillatory motions have not yet been thoroughly validated.

Bennetts and Williams (2015) presented measured surge, heave and pitch motions of a solitary wooden disk for a subset of the incident frequencies and amplitudes used for their multiple-disk tests, as an addendum to their investigation of wave transmission through multiple disks. They compared the measurements to the predictions of the potential-flow/thin-plate model, and found the model is, in general, accurate. They showed the model was least accurate for a test in which strong overwash occurred. In particular, the model overpredicted the translational motions, surge and heave, and underpredicted the rotational motion, pitch.

Previously, Montiel et al. (2013a, 2013b) presented measurements of the flexural motions of a thin plastic disk in response to regular incident waves, as functions of the incident frequency. They used three thin disks, with $H/D = 2.1 \times 10^{-3}$ to 6.9×10^{-3}, and incident waves with lengths ranging from $\lambda/D \approx 0.63$–3.14, and two small steepnesses $ka \approx 0.03$ and 0.06. They compared the measurements to predictions of the potential-flow/thin-plate model. However, they used a vertical rod through the centre of the disk to suppress surge, and a barrier around the edge of the disk to prevent overwash.

Meylan et al. (2015) presented measurements of the surge, heave and pitch motions of a thin plastic disk, as functions of λ/D. They used a disk with thickness over diameter quotient $H/D \approx 3.8 \times 10^{-2}$, and incident waves with lengths ranging from $\lambda/D \approx 0.9$–12.3 and steepness ranging from $ka \approx 0.01$–0.3. They compared the surge measurements to predictions of the slope-sliding model. They showed the model predictions are accurate for incident wavelengths approximately greater than two floe diameters, for suitably chosen model parameters. However, they also used a barrier around the edge of the disk to prevent overwash. Thus, their findings do not imply the slope-sliding model will accurately predict the surge motion of a disk without a barrier.

McGovern and Bai (2014) presented measurements of the heave and a composite surge and drift of model floes made of paraffin wax. They tested a variety of shapes, including square, rectangular and triangular shapes, but not disks. They modelled thick multiyear floes, and hence used relatively large thickness over characteristic length, D_c, quotients, typically $H/D_c = O(10^{-1})$. They used regular incident waves with lengths in the range $\lambda/D_c = 0.1$–0.75, and steepness in the range $ka \approx 0.03$–0.28. They studied heave and composite surge-drift as functions of λ/D_c and $2a/\lambda$, but did not compare these results to model predictions. They noted the occurrence of overwash for large incident amplitudes and high steepnesses, and suggested it as a source of the reduced heave responses they found in this regime, which mirrors the finding of Bennetts and Williams (2015).

McGovern and Bai (2014) also presented measurements of the drift of their model floes. They compared the measurements to the predictions of Stokes drift theory. They found the theory slightly underestimates the measurements. This finding is consistent with that of Huang et al. (2011). Laboratory experimental studies of the drift of floes have also been conducted by, for example, Harms (1987) in a two-dimensional setting.

This study presents a far more thorough experimental investigation of the surge, heave and pitch motions of a thin floating disk induced by regular incident waves than given by Bennetts and Williams (2015), with respect to the resolution of the incident wave frequency and steepness. In particular, two to three incident steepnesses are considered for each incident frequency, and four to six steepnesses are considered for two incident frequencies to test the steepness dependence in two different wavelength regimes. This study uses an extended dataset to that used by Meylan et al. (2015), which includes motions of a disk without an edge barrier. The results for the disk with a barrier are used to infer the effects of overwash on the motions of the disk without a barrier.

Further, the experimental measurements are compared to the surge motions predicted by the slope-sliding model, and the surge, heave and pitch motions predicted by the potential-flow/thin-plate model. The comparison is used to estimate the limit of validity of the models and indicate phenomena they do not capture. The surge motions predicted by the two models are compared analytically and numerically in the long-wavelength regime.