

Mathematics of Sea Ice and Ice Sheets Proceedings

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Extreme waves–in–ice during a polar cyclone

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Waves-in-ice measurements are presented, obtained with a shipborne stereoscopic camera system in the Antarctic marginal ice zone during an extreme polar cyclone. Data show large waves, significant wave height $\approx 5\text{m}$ 45km in from the ice edge in 100% sea-ice comprised of pancake floes (60%) and interstitial frazil ice (40%), and linear wave decay ($\approx 0.72\% \text{km}^{-1}$). The dominant component of wave energy shifts towards longer periods as waves propagate deeper into sea-ice, the spectrum becomes narrower in frequency and broader in direction. Individual waves up to 8m high are observed $\approx 50\text{km}$ in from the sea-ice edge, the largest wave measured in 100% sea-ice, but consistent with occurrence probability predicted by linear wave theory. Measurements reveal that waves-in-ice interactions remain intense in 100% sea-ice.

Eigenfunction expansion for velocity potential for flexural gravity waves during wave blocking

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During the last two decades, there has been significant progress in the literature on the interaction of surface gravity waves with large floating structures as well as floating ice. A great deal of effort has been made in studying, designing and installation of very large floating structures (VLFS) for utilisation of ocean space. Before the construction and positioning of any VLFS, careful and detailed studies are needed to investigate the hydrodynamic and hydroelastic behaviour of the VLFS. For simplicity, both ice sheet and very large floating structures are modelled as a thin elastic plate and semi-infinitely long in comparison with the wavelength of the incident wave. Since the floating runway is very long and wide, the draft is assumed to be small, and hence the structure behaves like a thin elastic plate. Under the assumptions of linear water wave theory and small amplitude structural response, Euler-Bernoulli beam equation in one-dimension is used for structural analysis. Consequently, the boundary condition on the flexible structure becomes fifth order for the boundary value problem in which the governing equation is the two-dimensional Laplace equation. As a result, the boundary value problems associated with this class of problems are non-Sturm-Liouville type in nature, and the associated eigenfunctions are not orthogonal in the usual sense. The study has become more interesting in the context of blocking dynamics of flexural gravity waves. Within the limits of flexural gravity wave blocking and buckling, the coalescence of roots of dispersion relation occurs. Thus, in the context of blocking dynamics, the eigenfunction expansion for velocity potential associated with flexural gravity waves in a homogeneous fluid having ice-covered sea surface are revisited in both the cases of finite and infinite water depths. These eigenfunction expansions and characteristics of associated eigensystem are obtained by using Green's function technique and the use of Cauchy integral theorem. As an application of the expansion formulae, flexural gravity wave scattering due to a crack in a floating ice-sheet in the presence of compression is investigated. Various physical quantities of interest such as the plate deflection, stain on plate and shear force on the plate are analysed numerically to understand the role of compressive during wave blocking.

Flexural gravity wave propagation in two-layer viscous fluid flows

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The characteristics of flexural-gravity wave propagation in a two-layer Newtonian fluid are investigated using the method of normal mode analysis. The fluid motion below the flexible structure is governed by the Navier–Stokes equation in both the layers, whereas the flexural wave dynamics is governed by the Euler–Bernoulli plate equation. The motion of the fluid is triggered by a uniform external shear stress applied on the surface of the upper layer. Using the linear perturbation technique and normal mode analysis, the Orr-sommerfeld system is obtained, which is solved to find the unstable modes. Numerical results suggest that the existence of a plate mode in addition to the interfacial mode, which becomes unstable at certain flow parameters. The dispersion curves, neutral stability curves, perturbed velocity, and plate deflection are investigated for different plate and flow configurations. It is noticed that the presence of a flexible plate suppresses the unstable surface mode and promotes the fluid stabilization. Further, the presence of external shear stress stabilizes/destabilizes the

flexural surface by destabilizing/stabilizing the interface as a consequence of momentum conservation. The findings of the present study help to understand the effect of viscosity and external shear on the flexural two-layer fluid flow.

Complex resonant ice shelf vibrations

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Ice shelves vibrate in response to ocean waves, and the resulting stresses and strains have been connected to rift propagation, calving, ice quakes and even catastrophic disintegration. An ice shelf vibration model is considered in which the shelf thickness and seabed vary over distance. It is shown that both the spectral and temporal responses of the shelf to wave forcing can be approximated using so-called complex resonances. The complex resonances are connected with real-valued resonances when the shelf and sub-shelf cavity are uncoupled from the open ocean, and these are used as starting points for a homotopy to capture the complex resonances.

Characteristics of flexural gravity waves near blocking point in shallow water

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Sea ice is a major feature of the polar environments in the Arctic and Antarctic which covers almost 7 percent of the world ocean surface. In recent decades, the issue of global warming and sea-level rise has created enormous interest in the analysis of wave-ice interaction problems. The study has become due to the great variety of ice conditions ranging from grease ice (behaving similarly to a floating layer of highly viscous fluid) to land-fast ice (behaving as a thin elastic plate). The thin plate model is also being used in the hydroelastic analysis of very large floating structures used for ocean space utilization. The role of axial forces with/without current on the hydroelastic analysis of these structures has to lead to the study on blocking dynamics of flexural gravity waves. The phenomenon of wave blocking and the associated phenomenon is leading to a class of eigenvalue problems in which the eigensystem possesses non-distinct eigenvalues since the corresponding wave dispersion relation possesses multiple propagating modes. In the vicinity of the blocking point, the potential energy increases in magnitude and the kinetic energy reduces to balance the energy conservation law and so the usual ray approximation is not valid for analyzing the wave characteristics near the blocking point.

In the present study, the characteristics of the flexural gravity waves with variable compression in the immediate neighborhood of the blocking point are analyzed using long-wave approximation. The physical problem is analyzed under the assumption of small amplitude structural response in the two-dimensional Cartesian coordinate system. It has been shown that the wave amplitude satisfies the hyper-Airy differential equation in the presence of variable compressive force, which is solved analytically in terms of generalized Airy function. Moreover, the asymptotic solution of the hyper-Airy differential equation is derived by employing the WKB method to match the far-field solution with the near-field solution. As a special case, it has been derived that at primary and secondary blocking points, the wave amplitude satisfies the well-known Airy differential equation. The analytically obtained result is validated with time-domain simulation using the spectral method. The study reveals that in the vicinity of the blocking point the wave is reflected back and so no transmission takes place. In the vicinity of the blocking point, the motion is independent of time, therefore the wave amplitude of incident and reflected waves are the same. Moreover, with the change in flexural rigidity, the blocking point shifted to higher or lower wavenumbers.

The effect of compressed ice-shelves on acoustic-gravity wave (AGW) propagation in an ocean having elastic floor

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Acoustic-gravity waves (AGW), the results of slight compressibility of water, have a vertically oscillatory profile in contrast with the gravity waves, which have exponential vertical profiles. A first few evanescent modes of gravity waves become real-valued to generate AGW. These waves spontaneously occur in the ocean due to an abrupt movement inside the water, such as a submarine earthquake. These waves travel much faster than the Tsunami waves and can be treated as an

early warning for Tsunami. The physical problem considered here will include an ice-cover (in the form of ice-shelves) at the ocean surface under the influence of in-plane compression, and the ocean bed consists of an elastic material of infinite depth. A boundary value problem will be formulated with the help of linearised water wave theory along with the boundary conditions prescribed at the ice-cover surface and the ocean floor surface. This work aims to obtain the velocity potential function and the dispersion relation the wave modes follow to analyze the generation of AGW and its phase speed. The phase speed of different AGW modes will be graphically illustrated juxtaposing with their counterparts when the ocean bottom is rigid. The impact of ocean bottom elasticity and that of the ice-cover on the AGW will be discussed.

A physical model for the sea ice drift imposed by ocean waves

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Laboratory experiments were conducted to examine the wave-imposed drift of modeled ice floes which are much smaller than the wavelengths. Results show that surge amplitudes and drift velocities of single ice floes decrease by increasing the incident wave frequency. Drift velocities of single ice floes are greater than or equal to classical Stokes drift, and in agreement with the research background.

An ice cover consisting of multiple ice floes in a high ice concentration tends to expand to one layer of ice floes by forward drifting of its front edge and backward drifting of its rear edge at the same time while the forward drift is faster than the backward drift. The resulting one layer of ice floes then entirely drifts forward as a whole body of an ice cover. The proposed methodology in the present study can estimate collective surge amplitudes and drift velocities of the ice cover, consisting of multiple ice floes. Collective surge amplitudes and drift velocities of the ice cover can be less than or equal to surge amplitudes and drift velocities of single ice floes. Collective surge amplitudes and drift velocities of the ice cover decrease by increasing the incident wave frequency. Increasing the ice concentration decreases collective surge amplitudes and drift velocities of the ice cover.

Modelling ice shelf rifts with the extended finite element method

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Useful representation of through-cutting rifts is a long standing challenge in ice shelf and ice sheet system modelling. Rifts disconnect the ice continuum, affecting stress transmission in a time-dependent manner as they propagate. Rifts eventually become the boundaries of large tabular icebergs which account for the vast majority of calved ice volume, a process that accounts for half the total mass-loss of Antarctica. But empirical studies of these important features are challenging, due to the range of temporal and spatial scales involved, and rifts remain difficult to represent in models. In this work we present a framework for their explicit representation in an ice shelf model.

We use an extended finite element implementation of linear elastic fracture mechanics to simulate rifts, in which stress fields are imposed in elastic sub-domains by calculating equivalent nodal forces. The stress fields are retrieved from modelled ice flow from the Ice-sheet and Sea-level System model (ISSM) using rheological properties inferred from remotely observed viscous deformation. This approach has been verified using synthetic fields and analytical solutions. We present case studies here that serve as validation.

Modeling the geometry of melt ponds on Arctic sea ice

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In late spring and summer, small pools of meltwater on top of Arctic sea ice grow and coalesce to form kilometer-scale labyrinthine ponds. The resulting surface patterns of dark and light largely determine the solar reflectance and transmittance of the ice cover, which are key parameters in the climate system and upper ocean ecology. The fractal dimension of the pond boundaries transitions from 1 to about 2 as they complexify. We consider two models of pond geometry. First, the pond boundaries are modeled as level curves of random surfaces which represent snow topography. Then we describe

an Ising model, originally developed a century ago to understand ferromagnetic materials, adapted to melt ponds, where minimization of the system energy yields realistic pond configurations. Finally, we analyze the isoperimetric quotient as a proxy for fractal dimension to show that melt pond complexity increases in discrete steps as ponds connect through saddle points of the surface topography, viewed as a Morse function.

New methods for observing sea ice fragmentation and wave-ice interactions using satellite altimetry

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Sea ice is a heterogeneous, fragmented material - a myriad of individual floes. The floe size distribution (FSD) is a critical piece of what determines the thermodynamic and dynamic evolution of sea ice, particularly in the marginal ice zone (MIZ) where ocean surface waves come into contact with sea ice and can cause it to fracture. Until recently, measuring the FSD has only been possible through labor-intensive analysis of two-dimensional imagery, which is sparse, affected by cloud, and challenging to interpret. Surface waves and wave energies in ice, on the other hand, have mainly only been measured through intensive field campaigns or SAR image analysis.

Here I will present new developments for using radar (CRYOSAT-2) and laser (ICESat-2) satellite altimeters to produce global, high temporal-and-spatial-resolution data products of both the FSD and the wave field in ice. These two new methodologies allow for a simultaneous analysis of how waves interact and fracture the ice, accurate description of the MIZ extent, and permit comparisons with new sea ice models that produce coupled wave-FSD output. I'll show how defining examining waves-in-ice can produce different estimates of the MIZ extent than are typically made using passive microwave satellites, and examine initial comparisons with modeled output.

Vibrations of Ice Shelves

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In this talk, I will present a mathematical model to study ocean wave-induced vibrations of ice shelves. The model is based on linear elasticity for the ice-shelf and potential flow for the fluid. The resulting governing equations are solved using the finite element method using a modal expansion technique by expressing the displacement field as a linear combination of the in-vacuo modes of the ice shelf. The model is validated by comparison with the thin-beam theory. Finally, I will present a few results by considering real-life shelf-cavity profiles, extracted from the BEDMAP2 dataset.

Scattering of long waves by a semi-infinite ice sheet in the presence of bottom undulation

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The topic of my talk is on two-dimensional long wave scattering by a semi-infinite ice sheet in the presence of a single breakwater/trench under the assumption of shallow wave theory and small amplitude structural response. The solution of the associated mathematical problem is obtained using the eigenfunction expansion method and matching the velocity and pressure at the interface boundaries of the breakwater/trench and semi-infinite plate. Matrix multiplication is used to derive explicit expression for the reflection coefficient. It is observed that in the absence of semi-infinite ice-sheet, two cycle (here a cycle is referred as one complete full Bragg resonance) are completed in case of breakwaters whereas one cycle is observed in case of trenches irrespective of number of trenches/breakwaters. Further, in the presence of a semi-infinite ice-sheet, reflection by single trench/breakwater is oscillatory nature. Various results such as reflection coefficient on the structures will be computed and analyzed for various wave and structural parameters and breakwater position and configurations.

References

P. Kar, T. Sahoo, and M. H. Meylan (2020) Bragg scattering of long waves by an array of floating flexible plates in the presence of multiple submerged trenches, *Physics of Fluids*, 32(9), 096603.

Modelling of Elastic plate over the arbitrary bottom topography

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Interaction of obliquely incident surface water waves by an elastic plate situated at a finite distance from an arbitrary bottom is investigated using the linearized theory of water wave. Step approximation along with matched eigenfunction expansion is utilized to solve the associated boundary value problem. It is analyzed that arbitrary bottom topography can help to reduce the high wave impact on the elastic plate known as a very large floating structure (VLFS). Hydrodynamics quantities such as reflection and transmission coefficients, free surface elevation, and plate deflection are analyzed for various values of system parameters. This study helps coastal and marine engineers to design and protect the VLFS from high wave impact.

Water waves interaction with poroelastic plate floating over undulated bottom topography

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In the present study, surface gravity waves interaction with a poroelastic plate floating over undulated bottom topography is analyzed. To solve the associated boundary value problem, a coupled boundary element-finite difference method is used. To model the poroelasticity of the plate, the deflection of the plate is modelled using Euler-Bernoulli beam theory with appropriate modifications in flexural rigidity and plate mass density as mentioned in Smith et al. (2020). Further, the kinematic boundary condition of the plate is modelled using the Darcy's law of fine pore theory. Various results associated with the wave scattering and wave energy dissipation for a variety of plate parameters will be studied. Further, the effect of bottom undulations on the wave scattering by a poroelastic plate will also be discussed.

Viscoelastic effects in vertical impact on floating ice

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Vertical impact of a rigid blunt body onto a floating ice plate is studied. The problem is coupled, unsteady and two-dimensional. The liquid is inviscid, incompressible and of infinite depth. The ice floe is modelled as a thin viscoelastic plate of constant thickness. The plate edges are free-free. The upper surface of the plate is covered with a viscoelastic layer of constant small thickness and negligible inertia. The reaction force of this layer is given by a nonlinear and one-dimensional Winkler-Kelvin-Voigt model, which does not permit a contact between the rigid body and the ice plate. This soft layer may describe either physical properties of the ice surface, such as a layer of crushed ice in the impact place, or presence of snow on the ice. The rigid body suddenly starts to move downwards pushing the ice into the liquid through the soft layer. The impact velocity is constant. The hydrodynamic loads, ice deflection, bending stresses in the ice plate, and the impact loads are determined simultaneously during the initial stage of impact, when the ice and body displacements are small but the bending stresses in the ice are maximum. In contrast to many other studies of floating ice response to impact on it, we do not assume the impact loads but calculate them as part of the solution together with the regions, where the loads are applied. It is shown that the strains in the ice plate caused by the impact are weakly dependent on the characteristics of the soft layer but strongly on viscoelastic parameters of the ice.

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Viscous-elastic properties of sea ice: experiments and models

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Standard tests with vertical and horizontal sea ice cores and sea ice beams were performed in the cold laboratory of UNIS to observe effects of ice creep, relaxation and delayed elasticity. Elastic modulus of sea ice was also determined by acoustic method and from the tests with vibrating beams. The experiments were performed in temperature range from -5°C to -20°C . Main goal of the experiment was to calculate elastic and viscous rheological constants characterising sea ice behaviour in the vertical and horizontal directions. Similar tests were performed with ice cores of spray ice formed on the beach due to tidal changes of water level and wave spray. It was discovered that creep, relaxation and delayed elasticity are much stronger in horizontal samples and samples made of granular spray ice than in vertical samples. Linear combination of Maxwell and Voigt units including two elastic modulus and two viscous coefficients describes well experimentally obtained dependencies of stresses and strains from time. The rheological constants are calculated by the approximation of the experimental dependencies by the curves obtained in numerical simulations. It was shown that if elastic modulus in the Maxwell unit is greater than the elastic modulus in the Voigt unit then stresses in bending deformations with constant rate (e.g., in flexural strength tests with cantilever beams) are determined by the elastic modulus of the Voigt unit, while in cyclic deformation the elastic modulus of Maxwell unit can also be important depending on the frequency. Dispersion equation describing wave propagation below viscous elastic ice plate is derived and the influence of ice viscosity on wave damping is discussed.

A comparison of finite element and traditional finite difference schemes to resolve sea ice dynamics

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Subject of this talk are the mathematical challenges and the numerical treatment of large scale sea ice problems at high resolutions. The model under consideration goes back to Hibler ("A dynamic thermodynamic sea ice model", J. Phys. Oceanogr., Hibler 1979) and is adapted to nearly all earth system models. Sea ice is described as a two-dimensional thin layer on the ocean surface which follows a viscous-plastic material law.

At high spatial resolution (5 km and lower) the viscous-plastic sea ice model starts to develop Linear Kinematic features (LKFs) such as leads in the sea ice cover. The amount of simulated LKFs is impacted by the solver convergence (Lemieux et al. 2012, Koldunov et al. 2019) as well as by the underlying variable staggering (Mehlmann et al. in prep). In this talk we will answer the question if a spatial resolution gain can be obtained by using Finite Element approaches instead of the traditional Arakawa B and C grids that are used to discretize sea ice dynamics.

We describe a novel finite element approach on triangles which is equivalent to a CD grid staggering and discuss its stability and approximation properties. Further, we present a numerical study of a sea ice benchmark problem and discuss results obtained with the classical sea ice packages such as CICE, MITgcm, FESOM and ICON but also with academic software libraries using different finite element approaches. We compare the different approaches and analyze them with respect to computational efficiency and the capability of resolving physical sea ice properties.

Ocean wave attenuation in the Ross Sea marginal ice zone

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We report the analysis of wave buoy measurements conducted in the austral autumn and winter of 2017 during the Polynyas, Ice Production, and seasonal Evolution in the Ross Sea (PIPERS) voyage. Fourteen buoys were deployed in the advancing marginal ice zone (MIZ). A number of large wave events with significant wave height as high as 9 m were recorded. We analysed the attenuation of ocean waves with penetration in the MIZ and computed the rate of exponential decay as a function of wave period. We found that the attenuation rate peaks at about 8–10 s, consistently across the dataset. Analysis of the ice conditions (obtained from satellites or in-situ observations) reveals that fragmented sea ice composed of small floes attenuates ocean waves faster than continuous ice or an ice cover composed of large floes, suggesting inhomogeneities in the MIZ needs to be better quantified to predict wave attenuation rates.

Role of damped elastic foundation on the blocking dynamics of flexural gravity wave in shallow water

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In the last two decades there has been a significant interest in the hydroelastic study of floating/submerged structures which are of immense importance in the utilization of ocean space for various human activities. Plates are essential structural elements that are extensively used in various forms and configurations in numerous technical applications (e.g., civil/marine structures, air-crafts/space vehicles, nuclear reactors, MEMS devices). In recent times, efforts have been made to study the various aspects of wave interaction with floating or submerged flexible structures in two/three-dimensions where the ocean bed is assumed to be rigid. On the other hand, sea bed flexibility plays an important role in various branches of engineering and applied disciplines. In the context of flexural gravity wave, the dynamics of wave blocking due to compression with/without current are of significant interest in the recent decades. However, for some certain value of compressive force known as buckling limit of compressive force, the wave celerity vanishes and the group velocity become discontinuous at critical wavenumber that may lead to the plate collapsing. During wave blocking, multiple root coalescence take place.

In the present study, a mathematical model is developed for gravity wave interaction with an infinitely long thin elastic plate resting over an elastic and viscous foundation. The physical problem is analyzed in the two-dimensional Cartesian coordinate system using linearized long wave formulation. The thin elastic plate is modelled using Euler-Bernoulli beam equation. Due to the presence of free surface and flexible elastic bottom, there exist two propagating wave modes before blocking occurs. The study reveals that in the presence of viscous foundation due to viscous damping, the roots of the dispersion relation corresponding to the flexural gravity wave mode are all complex and therefore the wave propagation decays as the propagates. The blocking and buckling limit of compressive forces are derived with/without damping and it is found that due to damping there is a line of discontinuity in the corresponding dispersion graph. At the critical limit of compressive force and wave number, both group and phase velocity are zero in the presence of viscous damping and therefore plate buckling will not occur.

Experimental model of wave reflection and transmission by double floating plate

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The outer part of the polar ice cover, better known as marginal ice zone (MIZ), is the area where the most part of the interaction between ice cover and ocean waves takes place. Ocean waves penetrate the ice pack cracking it into ice floes (large pieces of floating ice), which can drift away from the ice pack and melt more easily. At the same time, ice scatters the incident ocean waves in a reflected and a transmitted part, reducing wave transmission and energy. In the MIZ ice can be found in the form of floes of different size and shape. Their concentration is maximum in the inner part of the ice cover, then it decreases moving towards the outer edge. Existing wave-floe models are based on the traditional thin-plate theory, which underestimates waves attenuation for the most energetic waves. A new laboratory model was presented to carry out additional wave-floe interaction tests, in order to better investigate the whole complexity of the phenomenon and to overcome the limitations of the existing models. In this model a thin plastic plate was tested under the action of incident waves with varying amplitudes and periods. Particular attention was put on evaluating the reduction of the wave transmission for clearly defined incident wave conditions, including non-linear effects responsible for the dissipation of a large amount of energy occurring in presence of large amplitude waves. Here we extended the model testing a double plate configuration, to investigate the wave attenuation in presence of multiple floes. Plates are tested in two different set-ups, one with edge barriers to restrict waves overwashing the plates and one without them. In both cases the plates are moored at the front and rear edges, to evaluate wave reflection and transmission without plate-plate collisions. Experimental results show that wave transmission decreases in the double plate configuration, in particular when overwash is allowed on the upper surface of the plate. In addition, differently from the single plate tests, the presence of a second plate produces relevant energy dissipation also in the case without overwash.

Wave propagation in continuous sea ice: an experimental perspective

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Ocean waves penetrate hundreds of kilometres into the ice-covered ocean. Waves fracture the level ice into small floes, herd floes, introduce warm water and overwash the floes, accelerating ice melt and causing collisions, which concurrently erodes the floes and influences the large-scale deformation. Concomitantly, interactions between waves and the sea ice cause wave energy to reduce with distance travelled into the ice cover, attenuating wave driven effects. Here a pilot experiment in the ice tank at Aalto University (Finland) is presented to discuss how the properties of irregular small amplitude (linear) waves change as they propagate through continuous model sea ice. Irregular waves with a JONSWAP spectral shape were mechanically generated with a very low initial wave steepness to avoid ice break up and maintain a consistent continuous ice cover throughout the experiments. Observations show an exponential attenuation of wave energy with distance. High frequency components attenuated more rapidly than the low frequency counterparts, in agreement with a frequency-cubed power-law. The more effective attenuation in the high frequency range induced a substantial downshift of the spectral peak, stretching the dominant wave component as it propagates in ice.

Estimates of spectral wave attenuation in Antarctic sea ice, using model/data inversion

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A model-data inversion is applied to an extensive observational dataset collected in the Southern Ocean north of the Ross Sea during late autumn to early winter, producing estimates of the frequency-dependent rate of dissipation by sea ice. The modeling platform is WAVEWATCH III(R); which accounts for non-stationarity, advection, wave generation, and other relevant processes. The resulting 9477 dissipation profiles are co-located with other variables such as ice thickness to quantify correlations which might be exploited in later studies to improve predictions. An average of dissipation profiles from cases of thinner ice near the ice edge is fitted to a simple binomial. The binomial shows remarkable qualitative similarity to prior observation-based estimates of dissipation, and the power dependence is consistent with at least three theoretical models, one of which assumes that dissipation is dominated by turbulence generated by shear at the ice-water interface. Estimated dissipation is lower closer to the ice edge, where ice is thinner, and waveheight is larger. The quantified correlation with ice thickness may be exploited to develop new parametric predictions of dissipation.

Characteristics of the eigensystems for wave-ice interaction problems in the context of blocking dynamics of flexural gravity waves

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The study of wave-ice interaction problems leads a class of boundary value problems satisfying higher-order boundary conditions on the structural boundary which are non-Sturm-Liouville type in nature. The thin elastic plate model based on Euler-Bernoulli beam equation is used to model the floating ice sheet which is also used to model the very large floating structure in the associated wave-structure interaction problems. The eigensystem for gravity wave problems follows the classical orthogonal relations and the associated eigenfunction expansion formulae are straightforward. Chronological development of the characteristics of the eigensystem for surface gravity waves, capillary gravity waves followed by flexural gravity waves will be briefly reviewed in both the cases of homogeneous and two-layer fluids in the water of finite and infinite depths. Moreover, the general forms of the expansion formulae for different wave-ice interaction problems will be briefly discussed. The recent study on blocking dynamics of flexural gravity reveals that the dispersion relation possesses double/triple propagating modes along with the occurrence of double and triple roots within the buckling limit. In the present talk, the recent developments on the expansion formulae, the characteristics of the associated eigensystem and the associated physical problems will be highlighted and future research scope will be briefly discussed.

Scattering of water waves by flexible porous breakwater in the presence of an elastic plate

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The hydroelastic responses of an elastic plate named as a very large floating structure (VLFS) placed at a finite distance from a vertical flexible porous plate under wave action is investigated in the context of linear water wave theory. The mathematical problem is formulated based on the assumption of small amplitude structural response. It is assumed that the porous plate is made of material with fine pores so that the normal velocity across the perforated porous plate is linearly associated with the linear pressure drop. The eigenfunction expansion matching method (EEMM) for multiple domains is employed to solve the boundary value problem. The performance of the vertical plate in mitigating hydroelastic response of VLFS can be enhanced by selecting optimal structural parameters such as plate length, position and porosity. The study shall be useful to ocean engineers engaged in the design and protection of very large floating structures.

Infragravity waves, edge wave modes and leaky waves under sea ice – fact or fiction?

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A long-duration data set of observations is reported, collected off the southeast coast of Sakhalin Island in the Sea of Okhotsk during a period when the ocean surface was free of ice and when it was covered in sea ice. Bottom-mounted pressure sensor time series reveal oscillations across a wide range of frequencies, extending from local wind-generated seas and swell through to diurnal tides, and including infragravity (IG) waves, trapped edge wave modes, leaky waves and coastal seiches and their harmonics. The presence of sea ice in the vicinity appears to have an unexpectedly appreciable effect – notwithstanding its usually modest thickness of between 0.5 m and 1 m, whether it exists as drift ice that forms in the northern parts of the Sea of Okhotsk which migrates south or as continuous fast ice that is affixed to the shore. Whilst altered dispersion and some attenuation would be expected to occur for wind waves and swell, the effects of sea ice are also detected at IG wave periods and consequently edge wave modes and leaky modes. Furthermore, modulation of the time series appears to be occurring. A conceptual model is proposed based upon the paper by Longuet-Higgins and Stewart (1962) to explain why the sea ice seems to influence a broader range of periods than established wisdom would suggest. Alternative possible explanations are discussed and others are certainly welcome.

Longuet-Higgins, M. S. and R. W. Stewart (1962), Radiation stress and mass transport in gravity waves, with application to 'surf beats', *J. Fluid Mech.*, 13(4), 481–504.

Rossby waves in the ocean covered by compressed ice

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We study in the linear approximation barotropic Rossby waves in the ocean covered by compressed ice. We derive the dispersion relation and analyse its dependence on the degree of ice compression and its flexural rigidity. The characteristic parameters of a wave-field the most sensible to the influence of ice cover are estimated and presented for the Earth and some other planets of the Solar system. The main conclusion is rather pessimistic as the influence of ice cover on Rossby waves in the typical situations are almost insignificant, albeit in some special conditions it may be important. Anyway, the theoretical results clarifying the possible influence of ice or any other elastic cover on water waves in a rotating fluid represent an interest, in our opinion.

Wave generation at oscillations of a cylinder in a fluid under an ice sheet near a wall

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In the linear treatment and two-dimensional formulation, a solution is obtained for the problem of the oscillations of a circular cylinder submerged in an ideal incompressible fluid of finite depth near a vertical wall. The ice cover is modelled by a thin elastic semi-infinite plate of constant thickness. Various boundary conditions at the edge of the plate are considered: a free or clamped edge. Different flow characteristics investigated: the added-mass and damping coefficients, the amplitude of deflection and deformation of the ice sheet, as well as the forces acting on the wall, depending on the frequency of oscillations and the input parameters of the problem. To construct the solution, we used the method of expansion of the potential of the fluid flow velocity in multipoles - potentials that satisfy the Laplace equation and all boundary conditions, except for the conditions on the body. Previously, such multipoles were obtained for the case of infinite ice cover (in the absence of a wall). To fulfill the conditions on the wall, multipoles are supplemented by additional potentials, which are constructed using the Fourier transform.

It is shown that in the presence of a vertical wall, the added-mass and damping coefficients oscillate relative to the curves that correspond to the cylinder under an infinite ice sheet in the absence of a wall. With decreasing distance of the cylinder from the wall, the period of their oscillations increases. The damping coefficients vanish at some frequency values that means the absence of radiation waves to infinity. With an increase in the thickness of the ice sheet and low frequencies of cylinder oscillation, the added-mass and damping coefficients decrease, and at high frequencies they increase. The amplitude of the vertical force acting on the wall in the case of a clamped edge of the ice sheet increases with increasing ice thickness. The amplitude of the dynamic component of the horizontal force at high frequencies is much larger in the case of a fixed plate than in the case of a free edge.

Measurement noise and the "rollover" of wave attenuation rates in sea ice

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The attenuation rates of waves propagating through sea ice are routinely determined from field observations using wave sensors at various distances within sea ice. A "rollover" of spectral attenuation rates is often inferred at high frequencies, in the "tail" of the observed wave energy spectra. This is counter to theoretical expectations that attenuation rates increase with frequency. We explore the possibility that the rollover is caused by noise in the raw wave data, which adds spurious energy to the tail of observed wave energy spectra. We find that the energy from noise is sufficient to explain the rollovers in several recent field experiments, spanning a range of conditions and instrumentation.

A Numerical Study on Dynamics of Flexible Floating Plates Using Smoothed Particle Hydrodynamics

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Dynamical response of floating plates under water-wave impact is an extensive research topic in offshore engineering and geophysics. One of the interesting physical phenomena in this type of problem is washing of the ambient fluid over the top plate's surface, known as overwash. Here, Smoothed Particle Hydrodynamics, a Lagrangian solver well-suited for free-surface and interfacial flows, is adopted for the fluid phase. At the same time, linear thin plate theory is used to describe elastic deformations of the plate. Two different elastic Young moduli, 250MPa and 2.5GPa, are examined. The numerical results reveal that the plate with the smaller Young modulus suffers less overwash than the other.

Sea ice forecasting with the neXtSIM-F platform

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We present here some results from the new sea ice forecasting platform, neXtSIM-F (neXt-generation Sea Ice Model - Forecast platform). The model uses the new Brittle-Bingham-Maxwell (BBM) rheology which consists of an elastic spring in series with a composite element that contains a dashpot and a frictional sliding element in parallel. We assimilate OSISAF concentration to correct the sea ice extent. Drift agrees well with observations, but there are some issues with thickening at the north-east Greenland and north Svalbard coasts. This contributes to quite a strong arch of ice forming between these two coasts and allowing too little ice to be exported through the Fram Strait. There are also some issues with the land-fast ice in the Laptev and East Siberian seas being too slow to detach from the coast.

Waves in an ice channel with a lead

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The flexural-gravity waves propagating in an ice channel with a lead of open water in the ice cover are investigated within the linear theory of hydroelasticity. The channel is of rectangular cross section. The ice sheet is clamped to the walls of the channel. The ice thickness of the ice plate is constant. Deflections of the elastic ice sheets are described by the linear elastic plate equation, and the fluid flow in the channel is assumed to be potential, and the profile of the wave running along the channel is taken to be sinusoidal. The problem is solved by the normal mode method. The dispersion relations and the phase speeds are derived and the profiles of the flexural-gravity waves transverse to the channel are found, together with the strains distributions in the ice cover. The effects of the width of the channel and the water depth on the phase speeds are studied to determine critical speeds of a vehicle moving along the channel. The strain distributions in the ice sheet are analyzed to determine the position of the ice fracture.

Hydroelastics of an array of circular floating porous elastic plates

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A theoretical model based on linear potential flow theory and an eigenfunction matching method is developed to analyse the hydroelastic interaction between water waves and multiple circular floating porous elastic plates. The water domain is divided into the interior and exterior regions, representing the domain beneath each plate and the rest, which extends towards infinity horizontally, respectively. Spatial potentials in these two regions can be expressed as a series expansion of eigenfunctions. Three different types of edge conditions are considered. The unknown coefficients in the potential expressions can be determined by satisfying the continuity conditions for pressure and velocity at the interface of the two regions, together with the requirements for the motion/force at the edge of the plates. Apart from the straightforward method to evaluate the exact power dissipated by the array of porous elastic plates, an indirect method based on Green's theorem is determined. The indirect method expresses the wave-power dissipation in terms of Kochin functions. It is found that wave-power dissipation of an array of circular porous elastic plates can be enhanced by the constructive hydrodynamic interaction between the plates, and there is a profound potential of porous elastic plates for wave-power extraction. The results can be applied to a range of floating structures but have special application in modelling energy loss in flexible ice floes and wave-power extraction by flexible plate wave-energy converters.