POAC'15
Trondheim, Norway

Proceedings of the 23rd International Conference on
Port and Ocean Engineering under Arctic Conditions
June 14-18, 2015
Trondheim, Norway

A HYDRODYNAMIC ANALYSIS TOOL OF FREE FLOATING ICEBERG IN OPEN WATER

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ABSTRACT
In areas relevant for oil and gas field developments where there is a possibility for encountering icebergs, proper assessment of iceberg drift, iceberg towing, and iceberg loads are needed. To assess those issues one may needs input on the hydrodynamic properties of an iceberg, such as added mass, wave drift coefficient, and first order wave response. Due to the complexity of the iceberg shape, it is difficult and very time consuming to model the wet surface of the iceberg manually in any hydrodynamic numerical software. The present paper focuses on the development of a numerical tool tailor made specifically to enhance the efficiency of the hydrodynamic analysis, from pre-processing, model development, main analysis in the hydrodynamic solver, and to post-processing of the results. A demonstration of the capability of the tool is given on an irregular shape iceberg with five different sizes in order to evaluate their hydrodynamic properties.

INTRODUCTION
Although the shape of an iceberg is evidently irregular, for experimental and numerical modeling purposes, regular shapes (such as tabular/cubical, spherical, prismatic, etc.) have been chosen deliberately for simplicity, see e.g. Arunachalam et al. (1987), Drover and Kenny (2012). The argumentation is that these regular shapes cover a wide range of realistic shapes, see e.g. Arunachalam et al. (1987). In fact, there has been quite a common practice to employ regular shape in order to obtain hydrodynamic properties, see e.g. Isaacson and McTaggart (1989 and 1990), Lever and Sen (1987), and Lever et al. (1990). The practice was due to assumption that such simplicity is not likely to affect the iceberg kinetic energy significantly (Isaacson and McTaggart, 1989 and 1990).

Unfortunately, presently it is difficult to ensure the validity of the assumption. The only justification for the use of regularly shaped models, seem to be described by Lever et al. (1991), where the results of a three-year field study to measure the wave-induced motion of icebergs are described. They confirmed that, within the measurement uncertainty, the wave-tank based velocities calculated for regularly shaped models do reflect the range of velocities observed for randomly shaped full-scale icebergs. However, as indicated in Lever et al. (1991), the measurement uncertainty contributes to ±40% on normalized velocities due to the lack of wave-buoy data. Furthermore, there was no iceberg profiling during the study, which then undermine any conclusion with regard the relationship between the shape of full-scale icebergs and their motion velocities. In any case, such an assumption introduces uncertainty to the calculated iceberg kinetic energy and eventually to the estimated iceberg impact load. This brief overview underlines the need for more accurate assessments of the hydrodynamic properties of irregular shaped icebergs.

The magnitude of an iceberg impact load against a structure strongly depends on the kinetic energy E_k that is available to be spent for crushing. The kinetic energy is a function of the mass M and the impact velocity v, see Eq.(1). The mass here should include the iceberg mass m and the added mass $A(\omega)$, which is a function of wave frequency, see Eq.(2).

$$E_k = \frac{1}{2} M v^2 \tag{1}$$

$$M = m + A(\omega) \tag{2}$$

For a free-floating body in water, the equation of motion can be written as follows

$$\left| m + A_{kj} \right| \ddot{\eta}_j + B_{kj}\dot{\eta}_j + C_{kj}\eta_j = F_k \tag{3}$$

Where F, A, B, and C are the wave excitation force, added mass coefficient, damping coefficient, and restoring coefficient, respectively. The subscript $k=\{1,2,3\}$ indicates the force components in the x-, y-, and z- direction and $k=\{4,5,6\}$ indicates the moment components along the same axis. The subscript j={1,2,…,5,6} indicates the rigid-body motion modes, which corresponds to surge, sway, heave, roll, pitch, and yaw modes.

The added mass and damping loads are steady-state hydrodynamic forces and moments due to forced harmonic rigid body motion in a still water, see e.g. Faltinsen (1993). The forced motion of the body gives acceleration to the water particles near the body, which create a standing wave system near the body. This part of the hydrodynamic force, which is proportional to the response acceleration, is called added mass force. The forced motion of the body also generates outgoing waves, which removes energy from the body's oscillations and dissipates its motion. This part is called wave damping force and proportional to the response velocity. The restoring forces are determined from hydrostatic and mass considerations. For free-floating bodies, restoring terms are present for the heave, roll and pitch motions only, see e.g. Journee and Massie (2001).

There exist numerical tools that can predict linear wave-induced motions in six degrees of freedom and subsequently wave induced loads on large volume structures. Panel methods are the most common techniques used to analyze the linear steady state response of large-volume structures in regular waves. DNV GL software Sesam HydroD is capable of handling this type of problem and estimates added mass and damping (DNV Software, 2013a). When using such software to analyze iceberg motions, an accurate representation of the irregular iceberg shape (as opposed to simple shape) and mass properties are needed.

The uncertainty in the kinetic energy calculation can be reduced by having a better estimate of the added mass. However, prediction of added mass is not trivial due to the complexity of the iceberg shape. When using Sesam HydroD to estimate wave motions, HydroD requires a panel model, which needs to be modeled in a pre-processor, for instance GeniE (DNV Software, 2014). Modelling an irregular shaped iceberg manually tends to be cumbersome and inefficient. In order to define a surface panel, the user must specify the coordinate of the points, which form the panel and then indicate which side of the panel is loaded by hydrodynamic pressure. For a simple and regular geometry, this should be no problem. However, for an irregular shaped iceberg, it can be indeed challenging. Therefore, an automatic solution in order to perform the plating procedure is needed.

The tool must be able to perform consecutively the development of panel model of iceberg in GeniE, the calculation of mass properties of iceberg, and the execution of hydrodynamic analysis in HydroD. In addition, the tool must also be able to extract the interesting/important results from the output file of HydroD and convert it into meaningful formulation.

So far, we have discussed the added mass only. As mentioned above, the kinetic energy is also a function of impact velocity. The impact velocity consists of the drift velocity (which is induced by current, wind, and wave) and the first order wave response velocity. The wave drift velocity and the first order wave response velocity can be determined by a proper hydrodynamic analysis together with the procedure on obtaining the added mass. Therefore, the same numerical tool is able to produce the wave drift velocity and the first order wave response velocity. Consequently, it should further reduce the uncertainty in the kinetic energy calculation.

The present paper focuses on the development of a numerical tool tailor made specifically to enhance the efficiency of the hydrodynamic analysis, starting from pre-processing, model development, main analysis in the hydrodynamic solver, and post-processing of the result. A study on an irregular shape iceberg with five different sizes in order to evaluate their hydrodynamic properties and loads is given as demonstration of the tool's capability.

OVERVIEW OF THE NUMERICAL TOOL

The numerical tool is intended to allow a quicker and more efficient hydrodynamic analysis, starting from pre-processing, panel model development in GeniE and hydrodynamic analysis in HydroD, as well as post-processing of the result. The scheme of the numerical tool is presented in Figure 1. In addition, the numerical tool should also be able to handle a large number of cases and send them to GeniE and HydroD in an efficient way. The term "case" here relates to a certain panel model of the iceberg with a specific shape and dimensions. A case can be assigned with a range of wave frequencies and a range of wave propagation directions, which is very important due to the fact that the iceberg is unsymmetrical. A number of cases can be of panel model with the same basic iceberg shape but then scaled to different sizes in order to see the relationship between the added mass and the variation in total masses and/or the dimensions of the iceberg.

The process starts from the input data, i.e. 3D profile of the iceberg. The 3D profile data can be obtained from full-scale measurement. The iceberg shape data usually consist of a set of coordinates representing the iceberg surface ordered as polygons, which connect vertices at equal level. Canadian Program of Energy Research and Development (PERD) iceberg shapes and geometry database is an example of iceberg shape data that is arranged in such a way; see Canatec et al. (1999). Unfortunately, it is not seldom that the points in the polygon are not regularly arranged. As mentioned previously, the panel model is formed by defining points surrounding the panel. Regularly interval points in the polygon are necessary to ensure the surface modelling runs well. Therefore, the original polygon(s) in each level needs to be modified (re-partitioned) in order to obtain regular points arrangement.

Based on the modified profile, a mass model is created and a surface model is developed. The mass model is read by the HydroD input generator to produce a macro for HydroD and the surface model is read by the GeniE input generator to produce a macro for GeniE. It is aimed that the user only needs to push the run-button once in order to perform the hydrodynamic analysis (no need to open GeniE and HydroD manually) for a large number of cases. GeniE produces FEM file, which together with HydroD macro is read by HydroD to perform the hydrodynamic analysis. The result is stored in WADAM1.LIS file. The output file is then read by the result extractor and subsequently by the result interpreter, which produce a basis for the model development of hydrodynamic properties and responses of free-floating icebergs in an open sea under ice-free conditions.

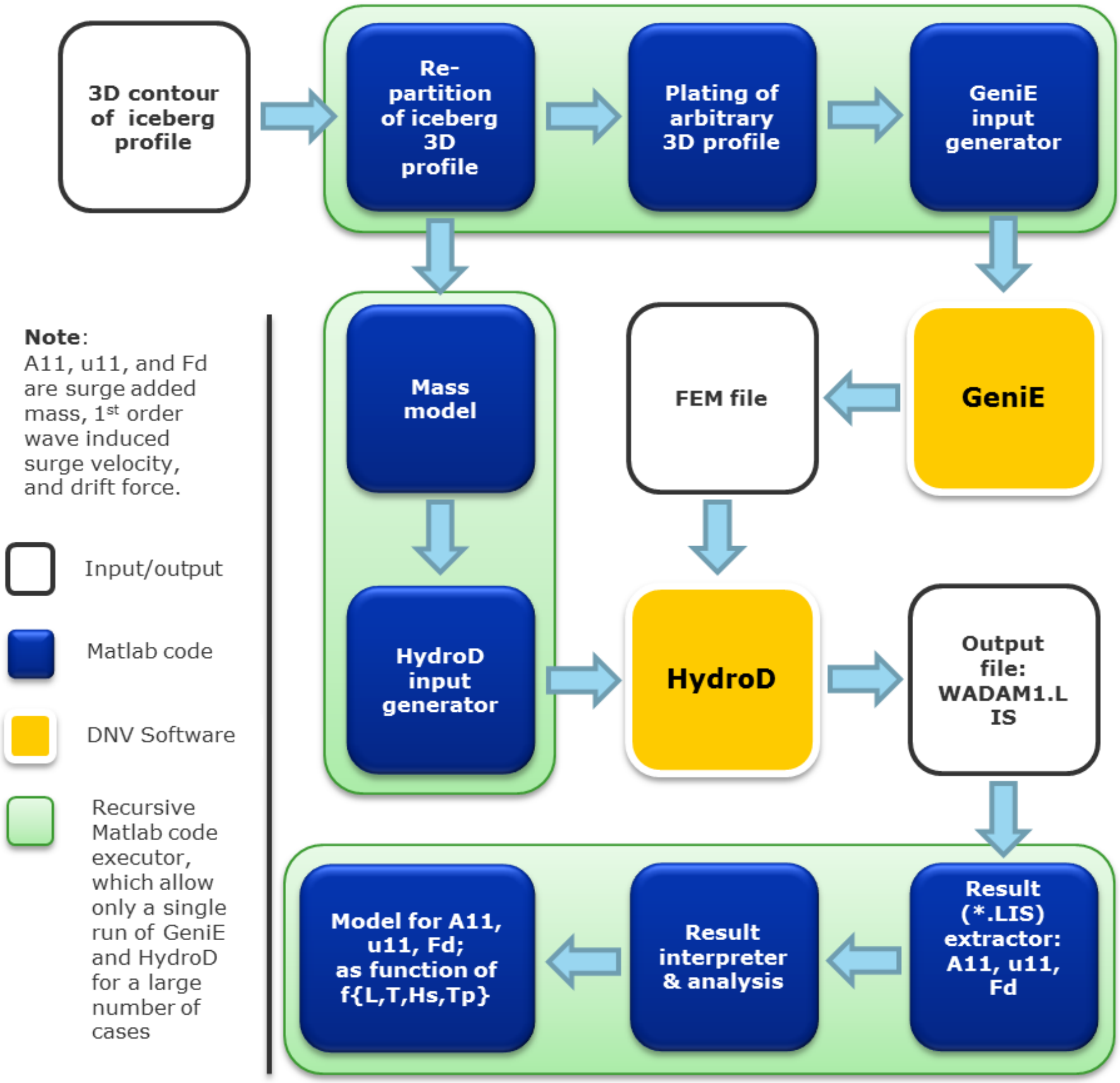

Figure 1. Scheme of the numerical tool.

SURFACE PANEL MODELLING

Other than automation, multi-software linkage, and recursive operation capability as its features, the tool has the surface panel modelling as its main engine. HydroD, as other hydrodynamic analysis software based on boundary element method, requires a panel model to run the hydrodynamic analysis. The panel model is usually prepared (built and meshed) in GeniE or other, such as Patran-Pre. Basically, the panel model contains information of the outer wall (surface) of the iceberg, which is defined by a set of surface panels. Here, the triangular panel is selected. Each triangular panel is defined by set of (three) vertices, which forms the triangular-panel and an assignment of which side is exposed to hydrodynamic pressure. Usually user performs such paneling operation manually in GUI environment. Considering highly irregular form of an iceberg, manual paneling operation can take intolerably long time. Therefore, an automatic surface panel modelling is desired.

The iceberg surface usually is represented by a collection of point coordinates, which is arranged as polygon(s) for the same level (at a specific vertical coordinate value). Assuming that each point in the polygon represents also the corner of the polygon, we may designate it as vertex.

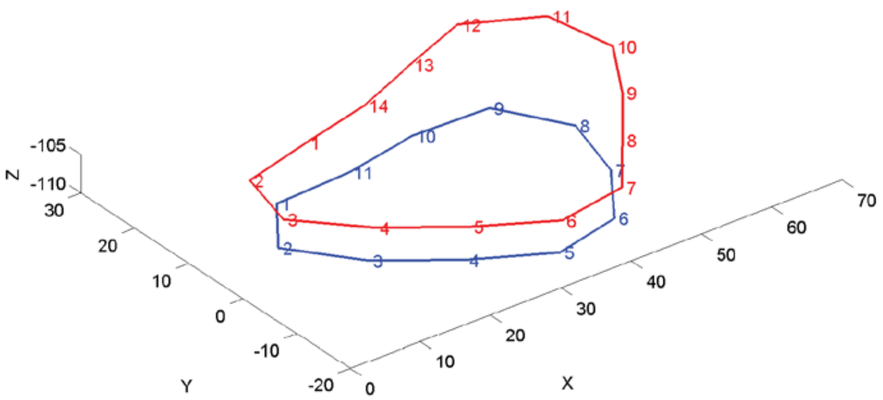

Figure 2. An example of a “slice” of an iceberg 3D-profile, it shows polygon at the lower and upper planes.

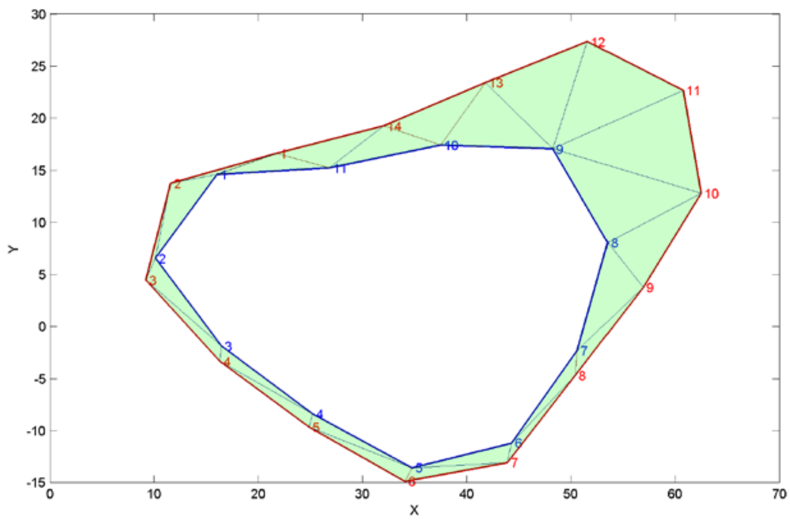

Figure 3. Typical triangular panel model after performing the modified Delaunay triangulation. Blue line indicates the lower polygon and red line indicates the upper polygon.

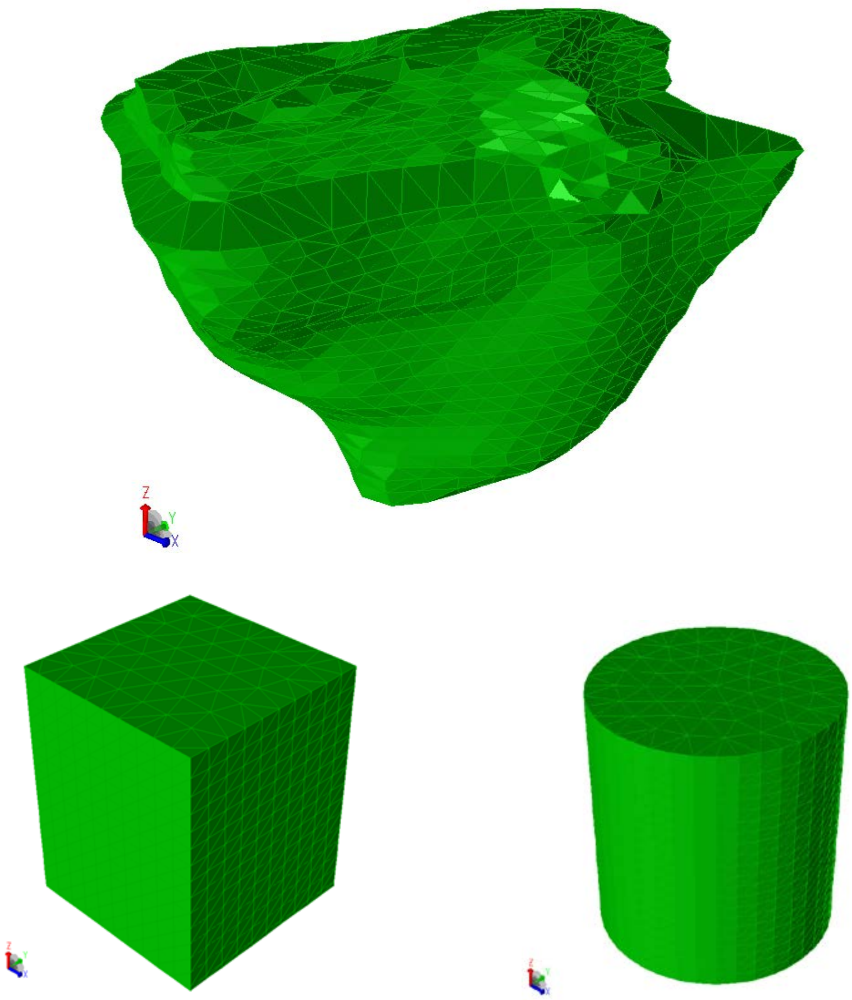

Figure 4. Example of surface panel model (captured from GeniE meshed view) for an irregular iceberg shape and regular shape of rectangular prism and vertical cylinder produced by the numerical tool.

The surface panel modeling is done by slice-wise approach. The term “slice” here refers to vertices at two consecutive X-Y planes (the lower and upper ones), where vertices on each plane form a polygon. An example of a “slice” of an iceberg 3D-profile is presented in Figure 2. The surface panel is generated for each slice, which then combined together with all other slices and the upper most and bottom most polygons of the iceberg 3D-profile in order to form a complete set of panels, which covers the whole surface of the iceberg.

As mentioned earlier, the triangular panel is selected as the surface panel model. A modified Delaunay triangulation is performed in order to build the triangular panel model. Delaunay triangulation ensures that the circumcircle associated with each triangle contains no other point in its interior. See e.g. Katajainen and Koppinen (1988) and Zalik (2005) for more insight into Delaunay triangulation algorithm. Figure 3 shows a typical triangular panel model for a “slice” after performing the modified Delaunay triangulation. The example of the surface panel modelling for an irregular iceberg shape and regular shape of rectangular prism and vertical cylinder are presented in Figure 4.

VALIDATION

The present numerical tool is developed in Matlab. The numerical tool executes HydroD to perform the hydrodynamic analysis. HydroD is actually an integrated program package for environmental modeling. The main engine of HydroD is Wadam (Wave Analysis by Diffraction and Morison Theory). Wadam is a general analysis program for calculation of wave-structure interaction for fixed and floating structures of arbitrary shape. For large volume structures, Wadam employs first and second order 3D potential theory, which is based directly on the Wamit program developed by Massachusetts Institute of Technology (DNV Software, 2013b). More information on Wamit, please consult e.g. Newman (1977), Newman and Selavounos (1988), and Wamit User Manuals Version 5.3S.

It is noted that during the impact, the iceberg is very close to the structure, such that the boundary effect could be important. Since potential flow theory cannot account for the behavior of flows that include a boundary layer, the result may not be accurate. Computation machine based on Navier-Stokes equations could be solution, which is beyond the scope of the present paper.

The validation of computer program is an important issue. A validation requires a variety of tests, which includes comparison with recognized analytical results and with independent computations for more complicated applications where no analytical results exist. Due to space limitation, validation study of Wamit is not presented here. The reader is advised to consult others. The first validation test of Wamit for simple body shapes (including spheres, spheroids, and axisymmetric cylinders) is reported by Breit et al. (1985). The validation test of Wamit for more complicated structure is reported by Korsmeyer et al. (1988), who investigated wave interaction with a six-column tension leg platform.

CASE STUDY

In order to demonstrate the capability of the numerical tool to perform hydrodynamic analysis of a real iceberg with complicated and irregular shape, a case study is performed. A real iceberg shape geometry was selected from PERD iceberg shapes and geometry database. The selected iceberg shape (contours/ 3D-profile) is then scaled into four other different sizes, i.e. 10%, 20%, 25% and 80% of its original size. See Table 1 for the iceberg dimensions and other properties. The reader may observe Figure 5 for the iceberg size comparison. It is noted that the figure serves for size comparison only. During the hydrodynamic analysis, an individual iceberg is treated separately, such that there is no shielding effect when the wave acting on the iceberg.

Table 1. List of the iceberg dimension and property.

Property	Ib#1	Ib#2	Ib#3	Ib#4	Ib#5
Size %	10%	20%	50%	80%	100%
L (m)	16	33	83	132	165
B (m)	13	26	76	115	152
T (m)	11	22	55	88	110
H (m)	3	6	15	24	30
Mass (Mton)	1.2	9.5	149.2	611.0	1193.5

Note:
L, B, T, H are the waterline length, the waterline width, the keel depth, and the sail height, respectively.

The study aims to obtain the hydrodynamic properties and loads, i.e. the added mass and the first order wave response velocity. In addition, how the magnitude of the hydrodynamic properties and loads varies with respect to different sizes and wave-heading angles is also studied.

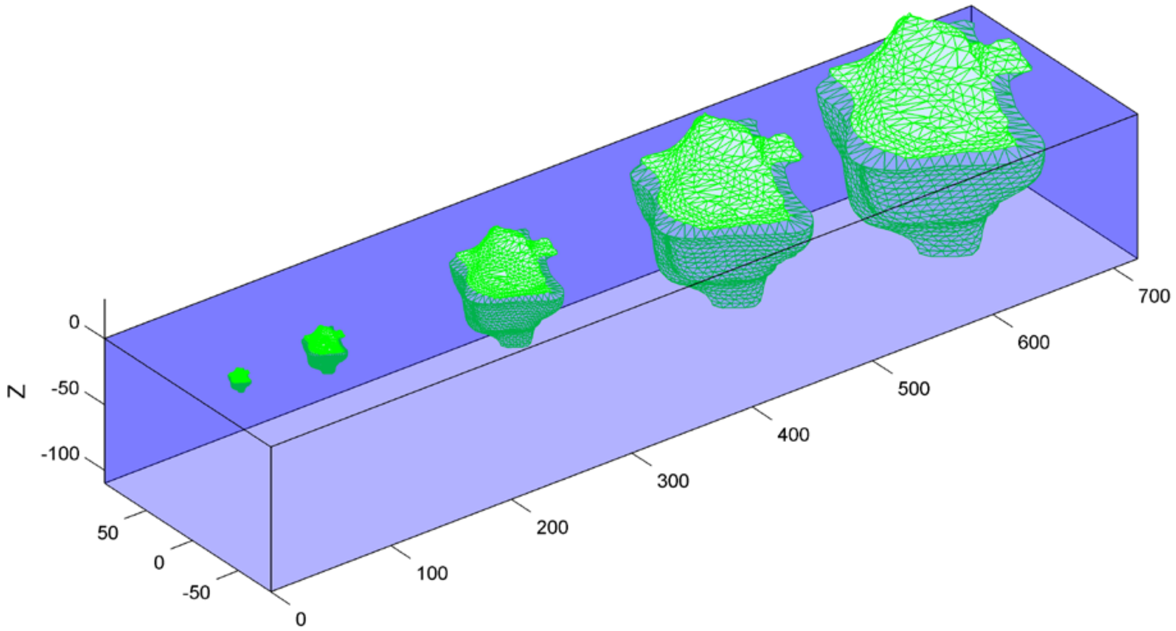

Figure 5. Case study: icebergs with the same geometry but different sizes. Note: the figure serves for size comparison only.

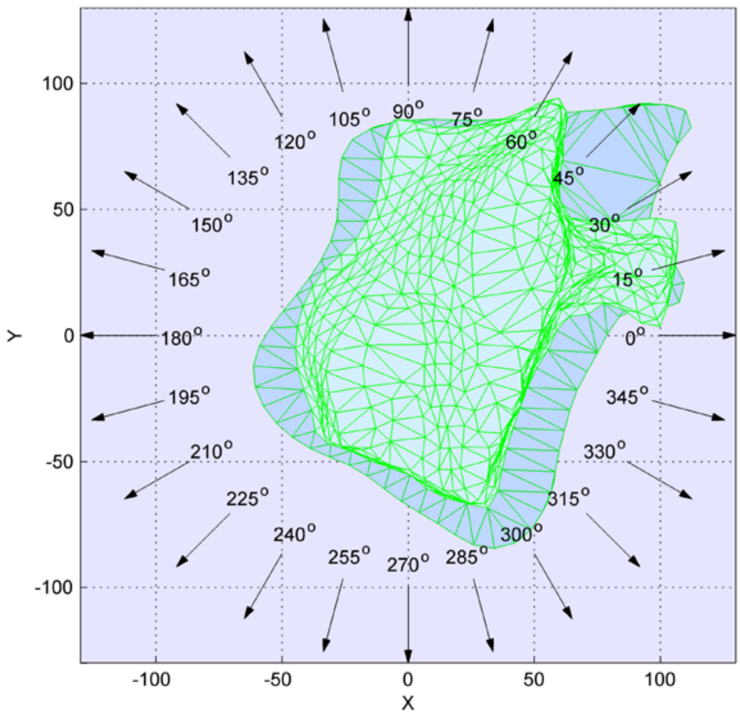

Figure 6. Wave heading angle, i.e. angle between positive X-axis and direction of wave propagation.

Added mass

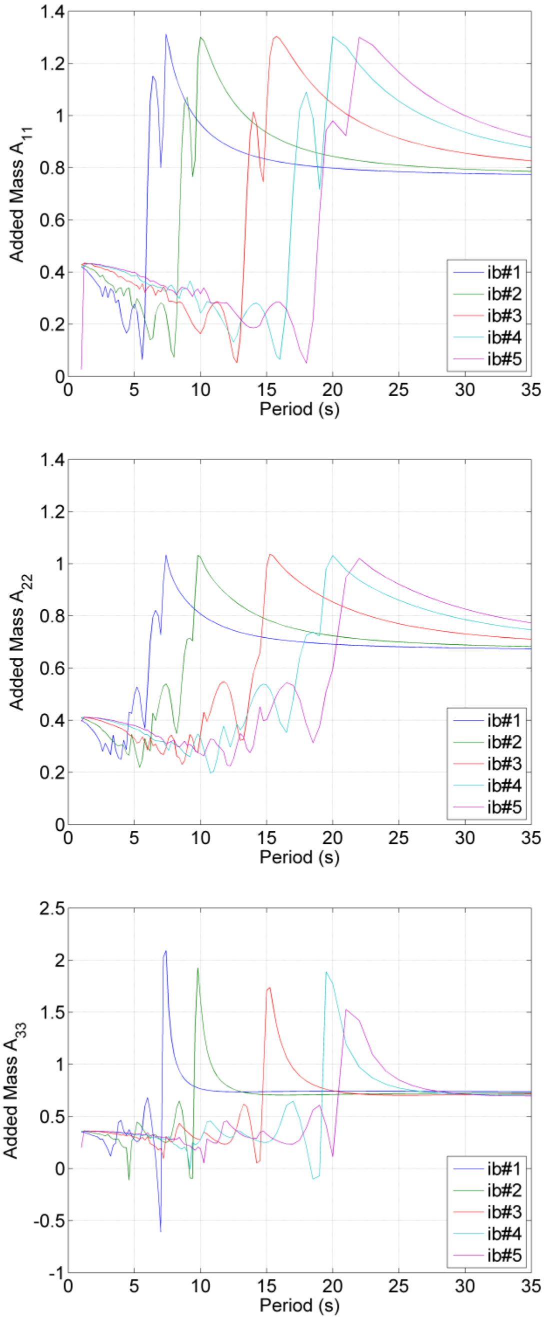

Figure 7. Added mass coefficient.

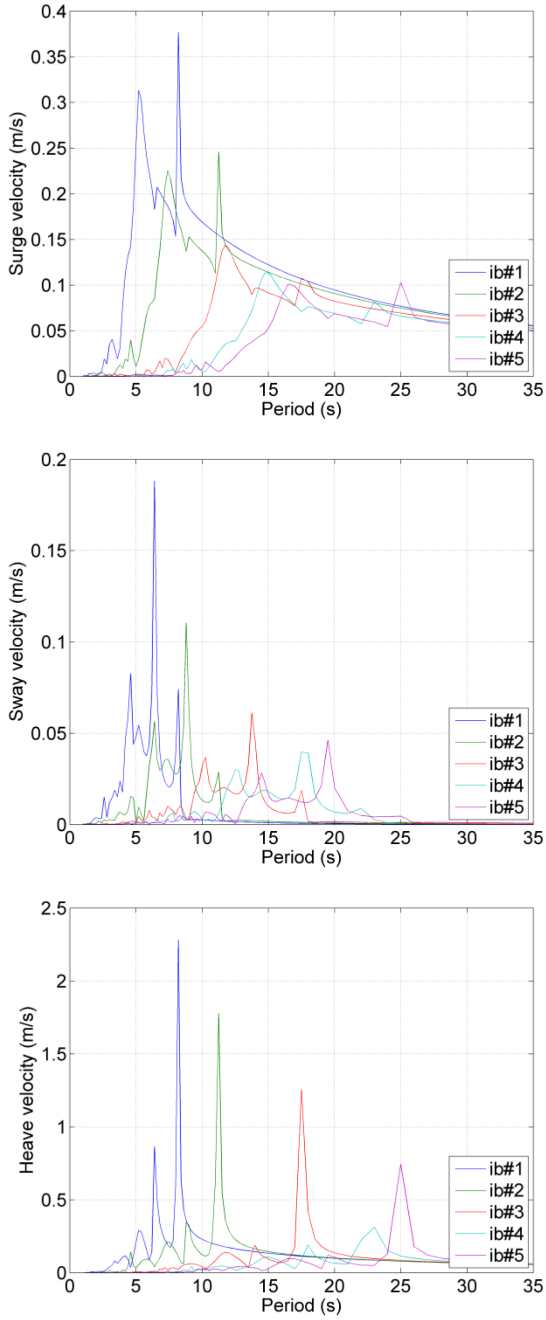

Figure 8. First order wave induced velocity per unit wave amplitude for heading angle 0^o.

The icebergs are exposed to wave actions, which propagate in 24 different heading angles (angle between positive X-axis and direction of wave propagation), see Figure 6. There is a set of 94 waves with different wave periods (i.e. between 1s to 35s) and a unit wave amplitude (ζ_a=1m) is employed. The analysis is aim for deep-water application (as such no bottom effect is considered) and therefore the water depth is set to 1000 meter.

It is noted that Figure 6 is a top-view. Here, we can observe the waterline. It is clear that the water plane area is considerably narrower than the plane further down, which is indicated by darker color. The cause for this maybe the iceberg has undergone significant wave action against its wall during its lifetime.

The added mass coefficient presented in Figure 7 has been normalized with its corresponding mass and mass moment of inertia. For this particular iceberg shape, the added mass in rotational modes, i.e. roll, pitch and yaw is negligible, and therefore they are not shown. We can observe in Figure 7 that the added mass is a function of wave period and the shame shape of iceberg exhibits similar curve of added mass coefficient. The only different is the wave period when the added mass peak coefficient is located, where it occurs at a quarter of the wave cycle, which is reasonable. This can be checked by converting the wave period into wavelength (by wave dispersion relation) and then take the ratio with the characteristic size of the icebergs. The peak added mass coefficient is approximately 1.3, 1.0, and 1.8, for surge, sway, and heave added mass, respectively. At low frequency, the iceberg size variation is almost negligible for all motion modes. The added mass coefficient in translational modes, i.e. surge, sway, and heave, converges to approximately the similar magnitude, i.e. 0.8±0.1. The minimum added mass coefficient can be taken as ± 0.4. For the iceberg kinetic energy estimation, the surge mode is maybe more interesting. The proper inclusion of surge added mass coefficient means 40%-130% higher kinetic energy. It of course depends on the dominant wave periods in the area. It also means that smaller icebergs tend to have higher added mass coefficient due to their early resonance periods.

First order wave induced velocity

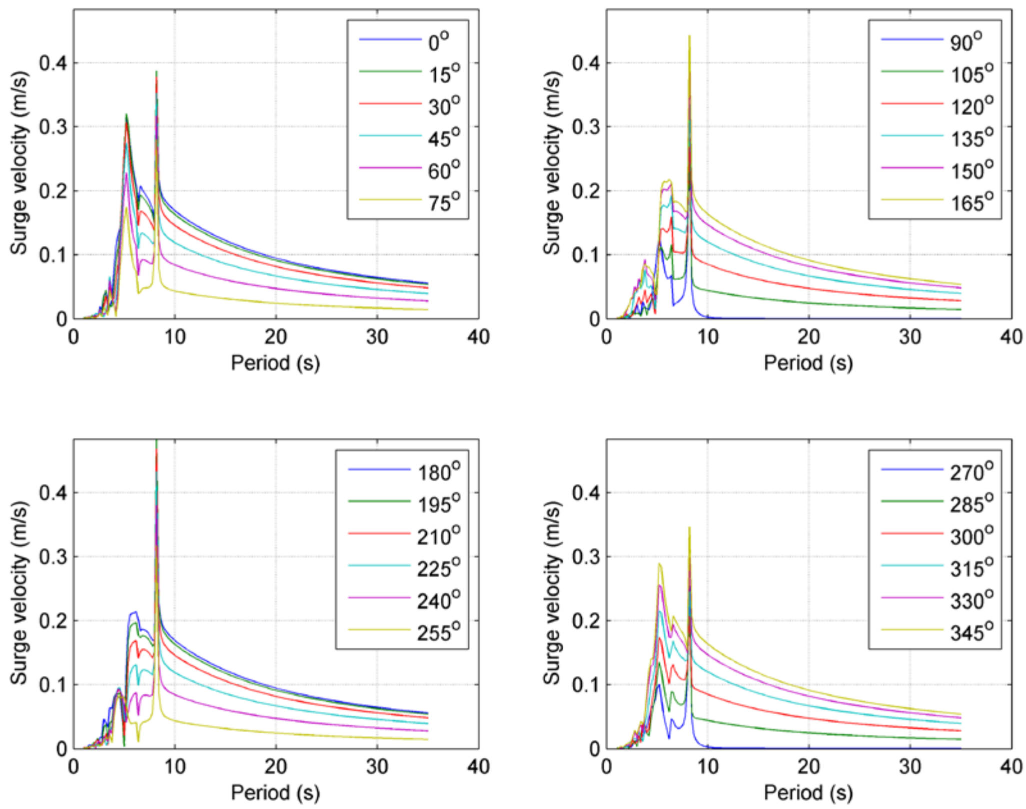

Figure 9. First order wave induced surge velocity per unit wave amplitude for iceberg #1 for various wave headings.

The first order wave induced velocity is actually not available from the HydroD output. Therefore, it should be derived from the first order wave induced motion as part of the post-processing effort. For this particular iceberg shape, the first order wave induced velocity in rotational modes, i.e. roll, pitch and yaw is negligible, and therefore they are not shown. It is clear that size has considerable effect to the wave induced velocity. The smaller the iceberg, it tends to have higher first order wave induced velocity. Again, it depends on the dominant wave periods in the area. For an example, for the smallest iceberg considered here with waterline length L=16m and mass of 1200 Kton, the first order wave induced surge velocity is 0.3 m/s for the wave period of 5 seconds. If typical iceberg drift speed is 0.5m/s, an increase of 60% forward speed means ≈2.56 times higher of kinetic energy! Due to unsymmetrical geometry of iceberg, different wave heading angle gives different wave induced velocity. This is demonstrated in Figure 9 for surge velocity.

CONCLUSION

The numerical tool tailor made specifically to enhance the efficiency of the hydrodynamic analysis of free-floating iceberg in open water has been described. A study on an irregular shape iceberg with five different sizes in order to evaluate their hydrodynamic properties and loads has been given as demonstration. The availability of the numerical tool is important to evaluate carefully the hydrodynamic properties and loads of various iceberg shapes. Due to scarcity of the full-scale measurement of wave induced iceberg motions, such an effort is valuable and cost effective in order to determine the hydrodynamic properties and load for a given iceberg size and sea state. Future study should also aim to quantify the uncertainty of the estimated iceberg impact load, which is introduced by the implementation of simplified shape.

ACKNOWLEDGMENTS

This work was carried out as a part of the BERGImpact project funded by DNV GL Strategic Research and Innovation. The author expresses his gratitude to the colleagues Per Olav Moslet, Erik W. Løkken, and Hege B. Thurmann, for their valuable comments and discussions.

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