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SHORT TERM MOTION ANALYSIS OF ICEBERGS IN LINEAR WAVES

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ABSTRACT

The need for the analysis of the motion of icebergs in waves is presented and the possible interaction effects between the iceberg and waves as well as its interaction with offshore structures is briefly discussed along with the hydrodynamic aspects involved in the analysis of wave induced motions of icebergs. A combined theoretical and experimental study for the estimation of the first order wave induced motions in surge and heave of a free floating iceberg in a regular wave field is presented. The theoretical model is based on the mathematical formulations of Garrison (1979) and Standing (1979) which employ a three dimensional source distribution technique. The computed model results have been compared with the previous analytical model and good agreement has been found. The computed results are then compared with the measured heave and surge motions of the model icebergs which agree quite well, within the limits of experimental error. The computational and experimental models are not meant to address in detail all the hydrodynamic aspects of wave interaction with a free floating iceberg. Only the oscillatory motions of icebergs have been computed and measured. The results indicate that the surge and heave velocity of model icebergs, with a draft to water depth ratio of less than 0.1 can be greater than 0.8 times the water particle velocity when the iceberg horizontal dimension is less than 0.3 times the wavelength. Additional computational and experimental model studies showed that the surge motion is reduced to less than 0.1 times the particle velocity when the draft to depth ratio is about 0.9 and the horizontal dimensions of the iceberg are increased to 0.5 times the wavelength. The heave motion for the same situation is reduced to about 0.5 times the particle velocity.

1. INTRODUCTION

The potential for collision with icebergs introduces unique challenges in the design of offshore structures, both fixed and floating, for the production of oil from the Hibernia field on the Canadian Eastern Seaboard. One of the requirements for the design of any offshore structure is the understanding of the interaction of the structure with the physical environment so as to accurately estimate the forces on the structure due to the interaction effects. Iceberg interaction with offshore structures has to be considered in the context of iceberg response to other environmental parameters. Most of the reported analytical studies on the interaction of icebergs with offshore platforms deal with the post impact scenario wherein the response of the structures due to impact loads is dealt with (Cammaert et al., 1983; Arockiasamy et al., 1984, 1985). In all these studies, the velocity of impact of the icebergs was assumed to be known.

The study of the interaction of icebergs with offshore structures is a complex phenomenon. In addition to the hydrodynamic interaction of the environmental parameters with both the structure and the iceberg, the physical and mechanical properties of both the iceberg and the structure come into play (Cammaert et al., 1983; Gammon et al., 1983; El-Tahan et al., 1984) in the overall design considerations of iceberg impact with offshore structures. At impact, the contact area fails and the failure progresses until the iceberg comes to rest or it is

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deflected away. The failure process itself is a function of the impact force, and the physical and mechanical properties of the iceberg in the region of impact. The magnitude of the impact force depends largely on the kinetic energy of the iceberg during impact (which depends on the velocity as well as the type of collision of iceberg with the structure (Bass et al., 1985) and the contact area (which varies with the shape of iceberg and structure profile) as pointed out by Cammaert et al. (1983). Additional information on iceberg interaction with offshore structures can be found in Russell et al. (1984) and Arunachalam et al. (1985). It is to be remembered that Cammaert et al. (1983) pointed out that an accurate estimation of the impact velocity of the icebergs is necessary for a realistic assessment of the study.

Icebergs are large floating bodies with varying shapes and dimensions, seldom resembling any regular shape. Icebergs have been classified, based on their above water shapes (when their underwater shapes were not readily available), as blocky, tabular, domed, pinnacled or dry-dock. Recent draft measurements of icebergs show that stable icebergs seldom have drafts greater than the water-line length (maximum horizontal dimension of the iceberg), as reported by Hotzel and Miller (1982) and Brooks (1982). Side scan sonar measurements of underwater profiles of icebergs (Buckley et al., 1985) confirm this. Although the shape of the iceberg is irregular, for experimental purposes, regular shapes can be chosen such that these shapes cover a wide range of realistic shapes. For example, spherical models, cubic models and prismatic models can be used to represent well rounded growlers and bergy bits, blocky icebergs and tabular icebergs, respectively.

2. BASIS FOR MOTION ANALYSIS OF ICEBERG

In the analysis of the motion or the velocity of icebergs, it would be ideal if the natural, irregular sea-state conditions with all the environmental parameters could be considered in the estimation of fluid loading so that all the observed physical mechanisms could be explained. Any attempt to deal with such a problem theoretically in its entirety is almost an impossible task, at least for the present time. However, experimental programs have been recently initiated to measure the wave induced motions of icebergs in natural sea states by Lever and Diemand (1985). It is worth mentioning that regular linear wave theory gives realistic estimates of the irregular sea states on the basis of spectral representation.

The environmental parameters that influence the motion of icebergs in an open seaway are wind, wave and current. Depending on the strength and direction of current in relation to the direction of wave propagation, the characteristics of the wave may be modified according to the relation given by Doppler shift (Hogben, 1976; Peregrine and Jonsson, 1983). However, Hogben (1976) based on North Sea experience, suggested that when the current speed is less than 15 percent of the celerity of the incident wave, the resulting wave characteristics are not significantly altered. Based on the data available for the design wave and current conditions for the Hibernia region (NLPD, 1981), the ratio of the magnitude of the current speed to the celerity of the design wave is about nine per cent and is well within the limiting criteria suggested by Hogben (1976). Therefore, in the estimation of the forces on icebergs for the Hibernia region, the fluid loading on the iceberg can be determined by the linear superposition of the individual contributions of wave current and wind. In the following pages, the motion of a free floating iceberg in a broad perspective is discussed, followed by the boundary value formulation of the problem and the computational method.

Analysis of the motion of the iceberg is important:

(1) To estimate the instantaneous velocity of the iceberg, comprising the drifting and oscillatory velocity, so as to estimate the kinetic energy at the time of impact of the iceberg on the offshore structure. In this case, the motion analysis is carried out over a short period of time, of the order of the wave period.

(2) To estimate the drifting path of the iceberg for offshore drilling operations. In this case, in addition to the major environmental parameters delineated above, other meteorological parameters such as the changes in temperature and barometric pressure may play an indirect role in the motion

analysis. Coriolis force should also be taken into account for such studies. This aspect of the problem has been addressed by various investogators (Sodhi and El-Tahan, 1980; Gaskill and Rochester, 1984; Hsiung and Aboul-Azm, 1982), although the driving environmental parameters assumed by these investigators varied from one to the other.

(3) To determine the stability conditions during the towing of icebergs.

A free floating iceberg in a regular wave experiences:

(1) First order oscillatory motions in six degrees of freedom, caused by the first order wave exciting forces.

(2) Steady horizontal drifting motion due to various second order effects.

The floating iceberg may also experience slow drift oscillations, in irregular waves in addition to the above two types of motions. However, it is not our aim to consider the irregular sea state in our analysis. Only regular linear waves will be considered.

3. LINEAR RESPONSE OF ICEBERGS IN REGULAR WAVES

In the estimation of the total motions of the floating iceberg in regular waves, it is necessary to estimate the first and second order forces at each time step of the process. The estimation of this instantaneous velocity remains the final aim of a current research effort between NORDCO, Memorial University of Newfoundland and the Institute for Marine Dynamics of the National Research Council of Canada, and the results will be reported elsewhere, shortly. However, in the present study, only the oscillatory motions of the iceberg will be discussed. The estimation of the first order forces has to be carried out in either case.

In this paper, the wave induced first order motions of model icebergs, in six degrees of freedom, under the influence of a regular wave field is presented. The measured surge and heave motions of the model icebergs are compared with the theoretically predicted values. The theoretical model is based on the mathematical formulations of Garrison (1979) and Standing (1979) which employ a three dimensional source distribution technique.

In order to predict the wave induced motions of the iceberg, it is essential to estimate approximately the various force components acting on the iceberg. While the hydrostatic forces on the iceberg can be estimated from its physical characteristics, the hydrodynamic forces, namely, the wave excitation forces and hydrodynamic reaction forces, may have to be obtained from potential theory formulations and the use of appropriate boundary conditions on both the fluid domain and the surface of the iceberg. Icebergs are large floating bodies having three dimensional characteristics. Hence, the application of potential flow theory can be justified, as the inertial forces will always dominate the drag forces under such conditions.

3.1 Mathematical formulation of free surface boundary value problem

The boundary value problem related to potential flows with a free surface is delineated below. The radiation and diffraction problems are formulated simultaneously. The iceberg is assumed to be a rigid and impervious body of arbitrary shape with a characteristic dimension (such as the half length of a rectangular prism) of a. It is assumed that the water depth is constant and finite and that the iceberg is finite in extent with its surface profile smooth so that the unit normal vectors are a continuous function.

3.1.1 The coordinate system

Let $Oxyz$ be a right handed co-ordinate system fixed in the fluid with Oz opposing the direction of gravity and Oxy lying in the undisturbed free surface of the fluid. Let $\bar{O}$ be the centre of gravity of the iceberg and let $\bar{O}\bar{x}\bar{y}\bar{z}$ be a co-ordinate system fixed at $\bar{O}$ and parallel to $Oxyz$ such that when the iceberg is in equilibrium, the co-ordinates of the centre of buoyancy and centre of gravity will, in the $Oxyz$ system, be $(O, O, -d_b)$ and $(O, O, -d_g)$ respectively. When the iceberg is in motion, the co-ordinates of a point $(\bar{x},\bar{y},\bar{z})$ in the $\bar{O}\bar{x}\bar{y}\bar{z}$ system will have the co-ordinates $(x, y, z+d_g)$ in the $Oxyz$ system. The co-ordinate system is explained in Fig. 1.

In the following pages a linearized boundary value problem is formulated for a three dimensionmal body of general shape in water of finite depth.

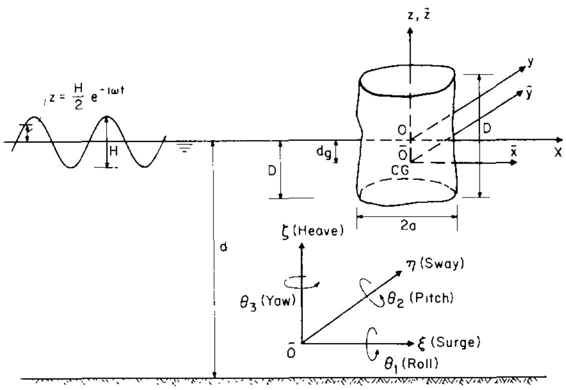

Fig. 1. Definition sketch.

Application of Green's third identity using Green's function that satisfies the free surface, bottom and radiation condition reduces the boundary value problem to the solution of an integral equation with the unknown function being the velocity potential over the surface of the body. The integral equation is solved for this using a numerical discretization procedure.

3.1.2 Hydrodynamic force calculations

It is assumed that:

(1) The fluid is inviscid and incompressible and the fluid flow irrotational. This implies that there exists a velocity potential Φ (x,y,z,t) such that the absolute velocity is given by $\nabla\Phi$. Since only regular harmonic waves are considered, Φ can also be written as Φ $(x,y,z,t) = \phi$ $(x,y,z)\exp(i\omega t)$, where ω=wave circular frequency ($2\pi/T$, t being wave period) and t=time.

(2) The waves are small amplitude linear waves.

(3) The linear and angular displacements of the iceberg are so small that the resulting motion of the iceberg may be obtained by linear superposition. This implies that the velocity potential due to diffraction can be formulated independently of the iceberg motion.

Hence the total potential can be expressed as:

$$\phi = \phi_{\rm i} + \phi_{\rm r} + \phi_{\rm d} \qquad (1)$$
$$= \phi_{\rm i} + \sum_{j=1}^{6} \phi_j + \phi_{\rm d}$$

where $\phi_{\rm i}$=velocity potential due to incident wave, $\phi_{\rm d}$=velocity potential due to diffracted wave, $\phi_{\rm r}$=velocity potential of the waves generated by the body motion, ϕ_j=components associated with each degree of freedom.

The incident velocity potential is given as:

$$\phi_{\rm i} = \frac{-{\rm i}gH\cosh\,[k(d+z)]}{2\omega\cosh\,(kd)}\exp\,[{\rm i}(kx\cos\beta + ky\sin\beta)] \qquad (2)$$

where β = direction of incident wave with respect to the x axis, g=acceleration due to gravity, H=wave height, d=water depth, k=wave number ($2\pi/L$, L being wavelength).

The three velocity potentials and hence, the total potential must satisfy the following conditions expressed as follows. The boundary conditions on the surface of the iceberg are expressible under the assumption of linear superposition. This implies that both radiation and diffraction problems are solved independently of each other. The conditions to be satisfied are:

(1) The continuity equation as given by the Laplace equation.

(2) The combined linearized free surface boundary condition, satisfying both the dynamic and kinematic conditions.

(3) The kinematic boundary condition at the horizontal impermeable seabed.

(4) The kinematic boundary condition on the surface of the iceberg, defining the diffraction problem.

(5) The kinetmatic boundary condition on the surface of the iceberg, defining the radiation problem.

(6) The radiation boundary condition, to have uniqueness of solution. This condition requires that the waves are outgoing and that at infinity only the incident wave is propagating.

3.2 Solution of boundary value problem

The solution of the boundary value problem delineated above by the use of integral equations is classical and has been dealt with by many investigators. Here, only a brief mention of the method essential for the solution will be given for the sake of completeness. For a more detailed account on this, the readers are advised to refer to Faltinsen and Michelsen (1974) and Hogben and Standing (1974).

An expression for ϕ_r and ϕ_d, that satisfy the appropriate boundary conditions, can be obtained using Green's identity and the source distribution technique as:

$$\phi_k = \frac{1}{4\pi} \iint_S f_k(\xi,\eta,\zeta)\, G(x,y,z;\ \xi,\eta,\zeta)\mathrm{d}S, \qquad (3)$$

where G = Green's function, $f_k(\xi,\eta,\zeta)$ = source distribution function for each mode of motion of iceberg.

The Green's function for a general wave satisfying all the boundary conditions except the one on the surface of the iceberg has been given by many investigators (see, for example, Hogben and Standing (1974)). Application of the kinematic boundary condition to eqn. (3) will result in an integral equation, namely the Fredholm integral equation of second kind given as:

$$-f_k(x,y,z) + \frac{1}{2\pi} \iint_S f_k(\xi,\eta,\zeta) \frac{\partial G}{\partial n}(x,y,z;\xi,\eta,\zeta)\mathrm{d}S = 2g_k(\xi,\eta,\zeta), \quad k=1,2,\dots,7 \qquad (4)$$

where g_k = specified complex function representing the magnitude of the normal component of velocity.

The above equation was solved by a numerical discretization procedure as discussed in Garrison (1979) to obtain the velocity potential. Using the velocity potential, the pressures, and hence, the wave exciting forces and the hydrodynamic reaction forces can be computed as follows. The hydrodynamic reaction pressures due to the iceberg motion, p_j, can be obtained as:

$$p_j = \rho\omega[\mathrm{Re}\{\mathrm{i}\phi_j \exp(-\mathrm{i}\omega t)\}], \quad j=1,2,\dots,6 \qquad (5)$$

where Re is the real part of the complex potential, ρ = density of water.

The pressure due to the incident and diffracted wave, p_7, is obtained as:

$$p_7 = \rho\omega[\mathrm{Re}\{\mathrm{i}(\phi_i + \phi_d)\exp(-\mathrm{i}\omega t)\}] \qquad (6)$$

The wave excitation forces and moments, F_j, can be obtained from eqn. (6) as:

$$F_j = \iint_S p_7\, h_j \mathrm{d}S, \quad j=1,2,\dots,6 \qquad (7)$$

where h_j = component of unit normal vector for the jth mode.

The forces and moments due to the motion of the iceberg, F_{ij}, can be obtained as:

$$F_{ij} = \iint_S p_j\, \mathrm{d}S, \quad i,j=1,2,\dots,6 \qquad (8)$$

From this, the added mass, A_{ij}, and damping, B_{ij}, coefficients can be obtained.

The mathematical formulation as defined above was used in developing a computational model. Details of the computer model are presented in the following section.

3.3 Equation of motion of iceberg

Using the computed wave excitation and hydrodynamic reaction forces the equation of motion of iceberg can be expressed in the following form as:

$$[-\omega^2(M_{ij}+A_{ij}) - \mathrm{i}\omega B_{ij} + C_{ij}]x_j = F_j, \quad i,j=1,2,\dots,6 \qquad (9)$$

where M_{ij} = mass of the iceberg, C_{ij} = hydrostatic reaction coefficient, x_j = amplitude of motion of iceberg in each mode.

4. DETAILS OF THE COMPUTER PROGRAM

A computer program "WAVETANK" was developed to compute the potentials, wave exciting forces and moments, added mass and damping and finally the amplitudes of the oscillatory motions of the iceberg under the conditions stipulated before. The program was written in FORTRAN code for use on a VAX/VMS system.

In the numerical discretization procedure, the surface of the body was divided into a number of rectangular panels. The number of panels describing the icebergs in the final runs was kept at 80 (the top surface not included). However, during the developmental stages of the computer program, the program was checked for the accuracy of the computed wave pressures on each panel and the total forces on a fixed body, by varying the number of panels from 80 to 125 and 180. It was found, considering the computational time involved for the increased number of panels with respect to the improvement in the accuracy of the computed essential parameters, that 80 panels would be sufficient. The computational time varied between 3 to 7 minutes of CPU depending upon the size of the body, water depth and wavelength for the 80 panel configuration. This is due to the fact that the number of terms that are used in the numerical integration of some of the terms involved in the estimation of Green's function may have to be varied (see Hogben and Standing, 1974) to reduce computational time.

4.1 Validation of the computer program

The computer program was validated against published results before using it for verifying the experimental results. The computer program was checked for the forces and moments on a floating rectangular dock (Yue et al., 1978) for various incident wave conditions. Fig. 2 shows the variation of the wave exciting forces in the x and y directions, in nondimensionalized form for a body with dimensions of 2 m×2 m×0.5 m in water of 1 m depth. The waves are propagating at a β value of $-\pi$. It can be seen from this figure that there is complete agreement of the estimated wave excitation forces as computed from the present computational model and the hybrid finite element model. Although the results of Yue et al. were for three dimensional body shapes, the data were restricted to only one ratio of draft to water depth. Hence, it was decided to check the program for different values of draft to depth ratios. In Fig. 3, the results of the wave forces on 3 rectangular model blocks of 0.8 m×0.8 m×0.8 m, 0.8 m×0.8 m×0.4 m and 0.8 m×0.6 m×0.3 m are shown. It is seen from the figure that the maximum horizontal force is roughly proportional to the draft of the block, provided that the horizontal dimensions of the floating model iceberg remained the same. These results were compared with the results of Garrett (1971), for the two dimensional diffraction of waves around circular docks. The results show very good qualitative agreement with the present one. Quantitative results cannot be obtained, because of the fact that the water depth and body dimensions were completely different and

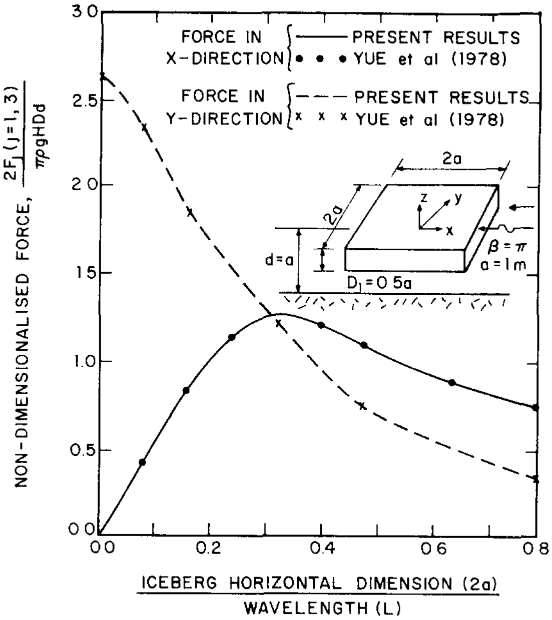

Fig. 2. Comparison of computed wave forces using the hybrid finite element method and the program "WAVETANK" (3-D source distribution method).

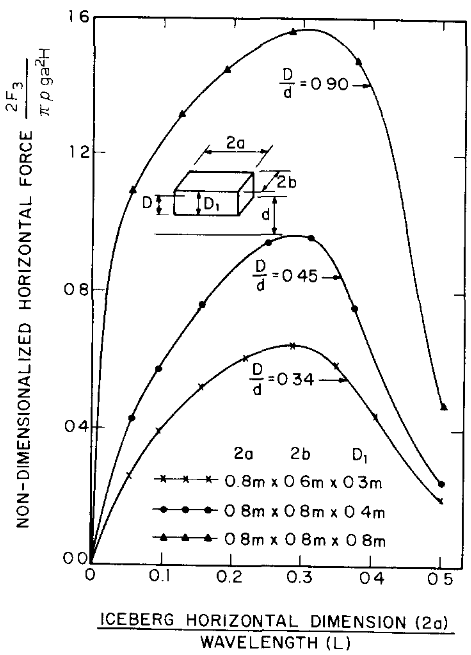

Fig. 3. Computed variation of normalized horizontal wave force on rectangular icebergs (3-D source distribution method).

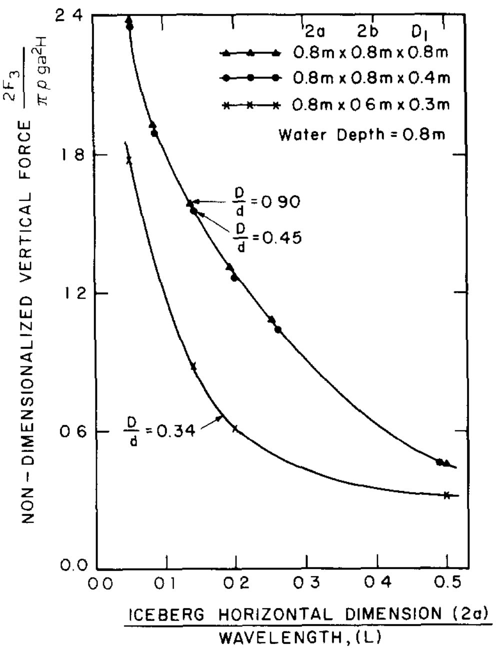

Fig. 4. Computed variation of normalized vertical force on different rectangular icebergs (3-D source distribution method).

that the circular dock of Garrett was not three-dimensional. Fig. 4 shows the computed wave forces in the vertical direction for various blocks mentioned above. It is found that as long as the horizontal dimensions of the floating body remains the same, the draft to depth ratio does not influence the vertical forces. This again is in qualitative agreement with the results of Garrett, within the restrictions mentioned above. Thus, it can be seen that in both cases the agreement between previous work and the present computational model study is good.

The program was also validated for the added mass and damping coefficients as well as the motions of rectangular prisms with the published results of Garrison (1979) and were found to be in good agreement.

5. EXPERIMENTAL PROGRAMME TO MEASURE SURGE AND HEAVE MOTIONS OF ICEBERG

The model studies were carried out in the wave-tow tank (see Fig. 5), at Memorial University of Newfoundland. Some of the problems associated with these studies and those of the numerical modelling are described in the following section.

5.1 A discussion on viscous effects on the numerical and physical modelling of iceberg interaction with waves

Since only the rigid body motions of the iceberg were to be measured, it was unnecessary to model the iceberg for its elastomechanical properties which, of course, should be taken into consideration for any impact analysis of icebergs with offshore structures. Hence, it was found necesary and sufficient for this study to use Froude scaling laws for the model studies. It is to be recognized, however, that both Froude and Reynolds scaling laws will have to be adhered to for a complete one to one correspondence between the model and the prototype. These are impossible to achieve simultaneously, for it can be shown from dimensional analysis that the fluid in the model system should have a kinematic viscosity of about 0.01 times the viscosity of sea water, for a scale factor of 20, which is not possible to achieve.

The problem of modelling the motion of icebergs is not only restricted to physical models. In fact similar problems are present in the numerical modelling. Part of the problem associated with modelling of viscous effects is the inability of the numerical models to properly take into account the real fluid effects as, for example, the generation, shedding and transportation of vortices.

Icebergs are large floating bodies which will make them less susceptible to drag forces if only their surface profile is regular and smooth. However, their irregular shape with sharp corners makes them vulnerable to vortex shedding. It is perceived that vortex sheet modelling, for wave structure interaction problems such as the one discussed for icebergs and offshore structures of a three-dimensional nature, would pose formidable problems at least at the present moment and any possible solution may have to wait for some more time to come. Numerical simulations are being attempted to improve the basic understanding of the fluid loading on offshore structure wherein the viscous effects can be incorporated. These models do not attempt, however, to

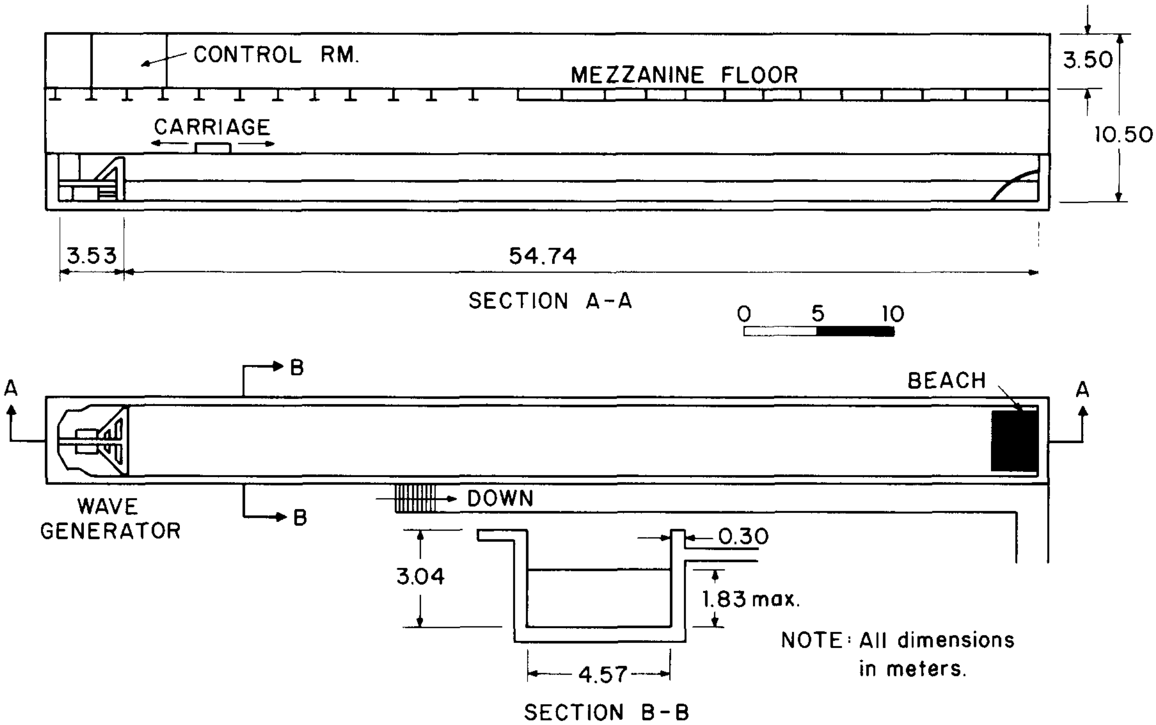

Fig. 5. Elevation and plan view of wave/tow tank.

solve the complete Navier-Stokes equation which by itself is impossible if one aims at a general solution. Instead, these numerical models assume that the vorticity is generated, shed and transported in thin sheets called the "vortex sheets", the flow outside these sheets being assumed to be inviscid and irrotational. These models show considerable promise (Stansby, 1977; Graham, 1978; Sarpkaya, 1979) in the basic understanding of the fluid structure interaction phenomenon from a purely fluid mechanical point of view. However, they are at present not able to provide a complete explanation of all the physical processes involved and hence cannot be employed as a design tool (Stansby, 1977). Besides, even for the simpler case of a two-dimensional steady or oscillatory fluid flow interaction with a structure, with a well-defined regular shape the vortex sheet models present a number of difficulties such as:

(1) The location of the separation point for any body other than a wedge shaped body.

(2) Numerical stability or instability of the discretized vortex sheets.

(3) Modelling of the convection of the shed vortices, their interaction with more than one vortex and their eventual dispersion.

Most of the model studies in the area of wave structure interaction have been carried out with the Reynolds number of the model being two to three orders of magnitude lower than that of the prototype. This is even true in the case of wave interaction with structures of small characteristic length, for which the drag forces could be of the same order of magnitude as the inertia forces, as expressed by the so called Morrison's equation. These studies concentrated on bottom founded structures as opposed to floating bodies such as icebergs. If the iceberg is small compared to the wavelength, the resistance to flow is less and hence the fluid particles around the iceberg are not likely to be accelerated relative to the motion of the iceberg even in the real world situation. Thus, the influence of viscosity may not be very important. Besides, it is well known that in the modelling of free surface wave phenomena, the gravity forces dominate the viscous forces, particularly when the characteristic dimensions of the body are comparable with that of the wavelength.

5.2 Experimental programme

The model icebergs were made of paraffin wax with a specific gravity of 0.90. Two different models (a cylinder with a diameter of 0.2 m and length of 0.2 m and a cube with sides of 0.2 m) were cast. The motions of the model icebergs were monitored by rotary potentiometers via a cable attached through their centres of gravity. This instrumentation was later replaced by a SELSPOT electro-optical system which provided six degrees of freedom motion response data that confirmed the results obtained using the original instrumentation. The wave profiles were monitored using a resistance type wave probe while the water particle velocities at the free surface were obtained using a Marsh-McBirney model 523M electromagnetic current meter. The model experiments were carried out at a constant water depth of 1.8 m and the wave period was varied between 0.8 s and 1.8 s, while the wave height was varied from 2.7 cm to 5.2 cm for each wave period.

Time series of motions of the model blocks and water particles were recorded on tape and the data analyzed later using a HP5451B Fourier analyzer. A detailed account of the experimental facility is provided by Muggeridge and Murray (1981). In the following section a comparison of the numerical and physical model for surge and heave motions is presented.

5.3 Comparison of experimental and computational models

The numerically verified computational model was used for the verification of the measured surge and heave motions of the iceberg. The model studies reported in the present study are for a wide range of ratio of draft to water depth. Fig. 6 shows the computed as well as the measured values of the surge motion of the model icebergs, for a draft to water depth ratio of 0.10, as a ratio of the amplitude of horizontal water particle velocity (u_0) against the ratio of the horizontal dimension of the model (2a) to wavelength (L). The figure also shows the data from recently published results of Lever et al. (1984) for similar draft to water depth ratios. It is seen that the agreement between the theoretical and experimental results is fairly good within the range of experimental error. It is also seen that the computed results also agree with the experimental results of Lever et al. (1984). From the figure, it is seen that the horizontal velocity (u) of model icebergs at the draft to water depth ratio of about 0.10 is greater than 0.8 times the horizontal water particle velocity, if the horizontal dimension of the iceberg is less than about 0.3 times the wavelength. When the horizontal dimension of the iceberg is more than 0.3 times the wavelength, the iceberg velocity reduces to a value of about $0.5u_0$. Fig. 7 shows the heave motion of the models for the same conditions as for Fig. 6. Here again the experimental results compare favourably with the computed values. The amplitude of heave velocity of the iceberg (v) for $2a/L$ values of less than 0.1 is almost equal to the

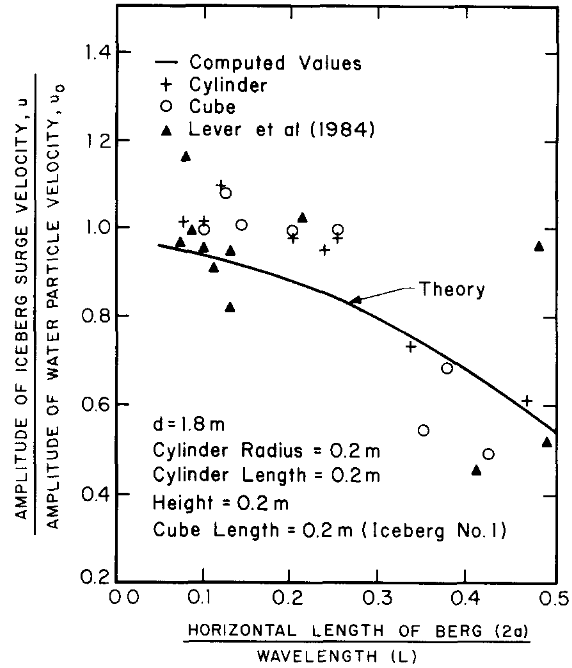

Fig. 6. Surge response of a number of model icebergs.

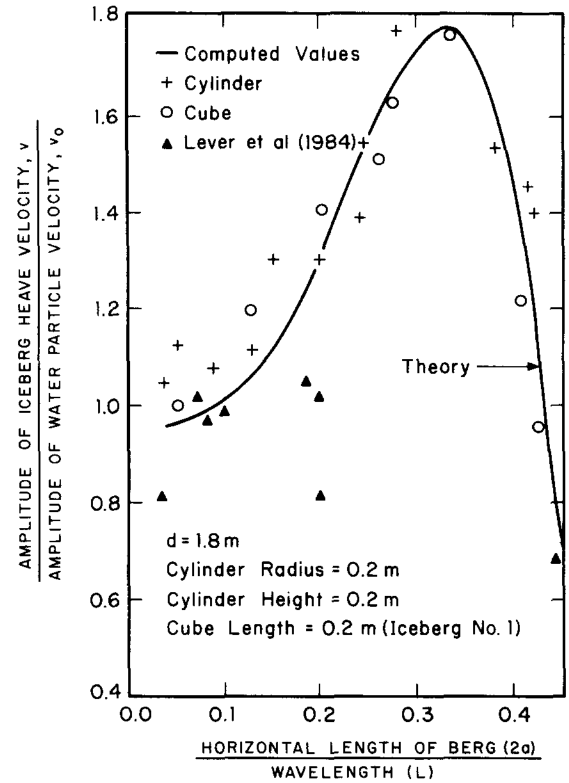

Fig. 7. Heave response of a number of model icebergs.

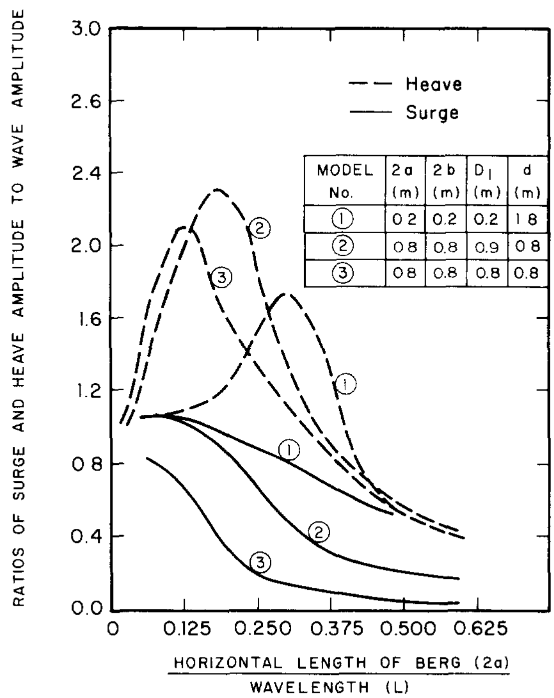

Fig. 8. Compute surge and heave responses of model icebergs.

amplitude of the water particle vertical velocity (v_0) both in the computational and experimental models. The heave velocity in the computational model increases for $2a/L$ greater than 0.1 and reaches a values of 1.8 times the water particle velocity when $2a/L$ is about 0.3 Beyond this value of $2a/L$, the value of v decreases very rapidly. The results of Lever et al. (1984) are also shown in this figure. Additional experimental results using a SELSPOT system showed motions similar to the one presented in Figs. 6 and 7 (NORDCO, 1985).

Further model studies with higher draft to depth ratios and with higher mass were carried out. The model dimensions are shown in Fig. 8 and the results for Iceberg Model No. 1, from Figs. 6 and 7, are also superimposed for purposes of comparison. The figure demonstrates the influence of both the horizontal dimension of the iceberg as well as its draft on the wave induced surge and heave motions. It is seen from this figure that the surge velocities are very much reduced for the larger models (models No. 2 and 3 have D/d values of 0.45 and 0.9, respectively) when compared with the previous model having a draft to depth ratio of 0.10. The model (No. 2) with a horizontal dimension of 0.5 times the wavelength has a surge velocity of only about 0.25 times the water particle velocity when the draft is about 0.45 times the water depth. When the draft is further increased to 0.90 times the water depth (model No. 3), while other dimensions of the model remain the same, the surge motion is reduced to about 0.10 times the water particle velocity. These motions are far less than those of the previous model (No. 1) originally shown in Fig. 6. Thus, the models with large draft to depth ratio no longer exhibit behaviour similar to that of a water particle. The heave motions show a similar response with the resonant frequency occurring at different conditions for different icebergs.

CONCLUSIONS

The need for the analysis of the motion of an iceberg in waves is presented and the assumptions involved in the reduction of the real world problem to one which can be treated mathematically and analyzed are clearly delineated. Good agreement was found between the present model and previous analytical and numerical results. The computed results are also compared with the measured heave and surge motions of the model icebergs. Within the limits of experimental error the surge motions agree well, although the heave motions are only satisfactory. It is to be realized that the computational model is not intended to completely address all the hydrodynamic aspects of wave interaction with a free floating iceberg. Only the oscillatory motions of icebergs have been computed and measured. The results indicate that the surge velocity of a model iceberg with a draft to water depth ratio of less than 0.1 can be greater than 0.8 times the water particle velocity when the iceberg horizontal dimension is less than 0.3 times the wavelength. As the horizontal dimensions of the iceberg and the draft to depth ratio is increased, the model iceberg no longer behaves like a water particle, the motions being much less than that of the water particles. The present studies show that the three-dimensional source distribution technique could be used for the estimation of forces and motions of a wide range of icebergs, with the restrictions as discussed earlier.

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LIST OF SYMBOLS

C_{ij} = Hydrostatic restoring coefficient
D = Draft of iceberg
d_g = Depth of submergence of the centre of gravity of the iceberg from the free surface
d = Water depth
f_k = Source distribution function for the floating body; $k=1,2,...,7$
F_j = Wave exciting force on the iceberg, $j=1,2,...,6$
g = Acceleration due to gravity
G = Green's function
H = Wave height
k = Wave number $=2\pi/L$
L = Wavelength
M_{ij} = Mass coefficient
p_j = Hydrodynamic pressure on the iceberg, $j=1,2,...,6$
T = Wave period
u = Amplitude of iceberg surge velocity
u_0 = Amplitude of horizontal water particle velocity
v = Amplitude of iceberg heave velocity
v_0 = Amplitude of vertical water particle velocity
β = Direction of incident wave with respect to x axis
ϕ_d = Diffracted potential due to the iceberg
ϕ_i = Incident velocity potential
ϕ_r = Velocity potential due to body motion $= \sum_{j=1}^{6} \phi_j$
ω = Wave circular frequency

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