Research on low and high speed hovercraft icebreaking

Michael Hinchey and Bruce Colbourne

Abstract: Operational experience in Canada during the early seventies showed that hovercraft can make very effective icebreakers. In a low speed mode, the hovercraft causes an air cavity to form under the sheet as it rides onto it. This causes a section of the sheet to become unsupported and fail in bending under the action of its own weight. In a high speed mode, the motion of the craft over the sheet sets up large amplitude flexural gravity waves. Research into both modes of operation has been going on at Memorial University of Newfoundland (MUN) since the mid-eighties. This paper summarizes this work. For the low speed case, scaling laws for the resistance to forward motion of two new geometries were developed and confirmed with data obtained in the ice tank at the Institute for Marine Dynamics (IMD) in Newfoundland. For the high speed case, measurements of sheet deflections in the MUN wave tank and the IMD ice tank showed that a critical speed exists for motion over a sheet. At this speed, sheet deflections are limited only by dissipation and nonlinearities. We believe this critical speed is the source of high speed mode hovercraft icebreaking.

Key words: hovercraft, icebreakers, air cavity mode, wave mode.

Résumé : Des expériences réalisées au Canada au début des années 1970 ont démontré que l'aéroglisseur pouvait jouer efficacement le rôle de brise-glace. Lorsqu'il se déplace à faible vitesse, l'aéroglisseur entraîne la formation d'un vide d'air sous la couverture de glace. Ce phénomène a comme conséquence qu'une section de la couverture se trouve soudainement sans appui et cède sous l'action de son propre poids. À grande vitesse, le déplacement de l'aéroglisseur produit des ondes de gravité en flexion de grande amplitude. Des recherches sur ces deux modes de déplacement sont effectuées au Memorial University of Newfoundland (MUN) depuis le milieu des années 80. Cet article en résume l'essentiel. Dans le cas du déplacement à faible vitesse, des lois de similitude pour la résistance au mouvement en avant de deux nouveaux modèles ont été développées et validées en fonction des données recueillies dans le bassin d'essais pour brise-glaces de l'Institut for Marine Dynamics de Terre-Neuve (IMD). En ce qui concerne le déplacement à grande vitesse, des mesures de déviation de la couche dans la cuve à houle du MUN et dans le bassin d'essais pour brise-glaces du IMD ont révélé l'existence d'une vitesse critique de déplacement sur une couche de glace. À cette vitesse, les déviations sont limitées par la dissipation et des caractéristiques non-linéaires. Les auteurs sont d'avis que cette vitesse critique est la source de rupture des glaces dans le cas d'un déplacement à grande vitesse.

Mots clés : aéroglisseur, brise-glaces, mode de propagation des vides d'air, mode de propagation d'onde. [Traduit par la rédaction]

Introduction

During the early seventies, operational experience in Canada showed that hovercraft can make very effective icebreakers. During trials in the winter of 1971 – 1972 near Yellowknife, N.W.T., the towed hovercraft ACT-100 broke ice about 0.7 m thick while moving at about 5 km/h. Similar performance was observed the following winter during simulated cable ferry trials across the MacKenzie River near Tuktoyaktuk, N.W.T.

In later trials the ACT-100 was mated with the bow of a regular icebreaker and operated in the Thunder Bay port area. On an energy consumption basis, this combination was found to be much better than the icebreaker acting alone. Its resistance to forward motion was much lower, and it broke ice at a faster rate. Typically, during operation, the water surface directly beneath the craft was depressed below the lower edge of the sheet, and an air cavity was formed which propagated away from the craft under the sheet. The sheet failed mainly because of bending stresses set up by the weight of an unsupported or overhanging section of the sheet inside the cushion. Unlike conventional icebreakers, a ship and hovercraft combination does little damage to port facilities, mainly because it exerts insignificant forces in the plane of a sheet.

This type of hovercraft icebreaking has come to be known as low speed mode icebreaking. It contrasts sharply with

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Fig. 1. Wave mode hovercraft icebreaker.

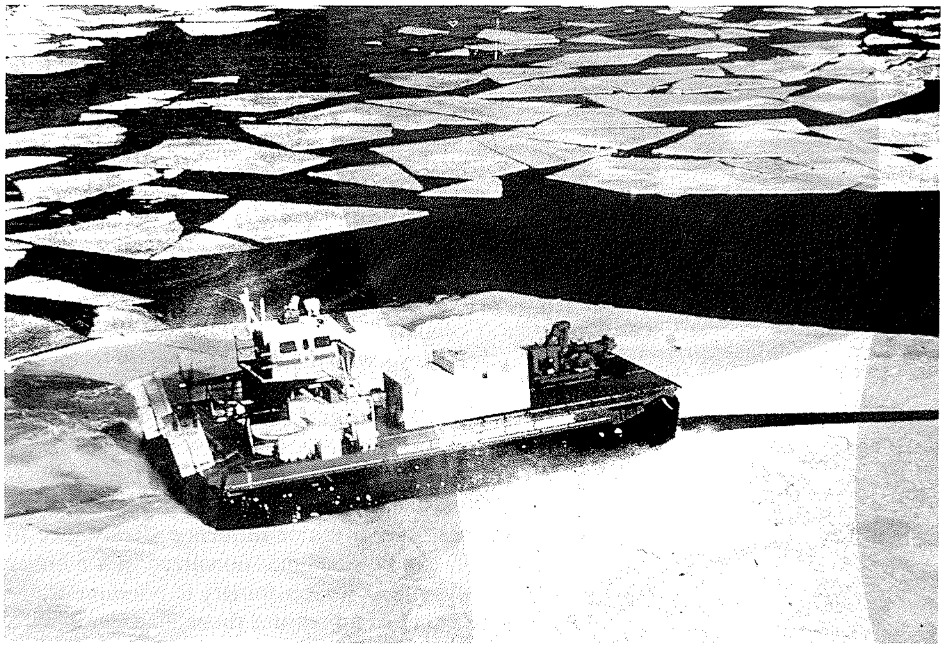


Fig. 2. Air cushion icebreaker bow.

another mode at high speed first observed during 1973–1974 winter trials of the Canadian Coast Guard Voyageur near Parry Sound, Ontario. During the high speed trials, the Voyageur (Fig. 1) broke, relative to low speed, ice twice as thick over a path three times as wide. It did this by setting up large amplitude flexural gravity waves. The Canadian Coast Guard has since used this wave mode for breaking ice on small rivers leading into the St. Lawrence River. This has most often been done during the spring thaw when flooding is a problem. Ice Control Enterprises, a private operator, has recently used the technique in the Chicoutimi region in Quebec.

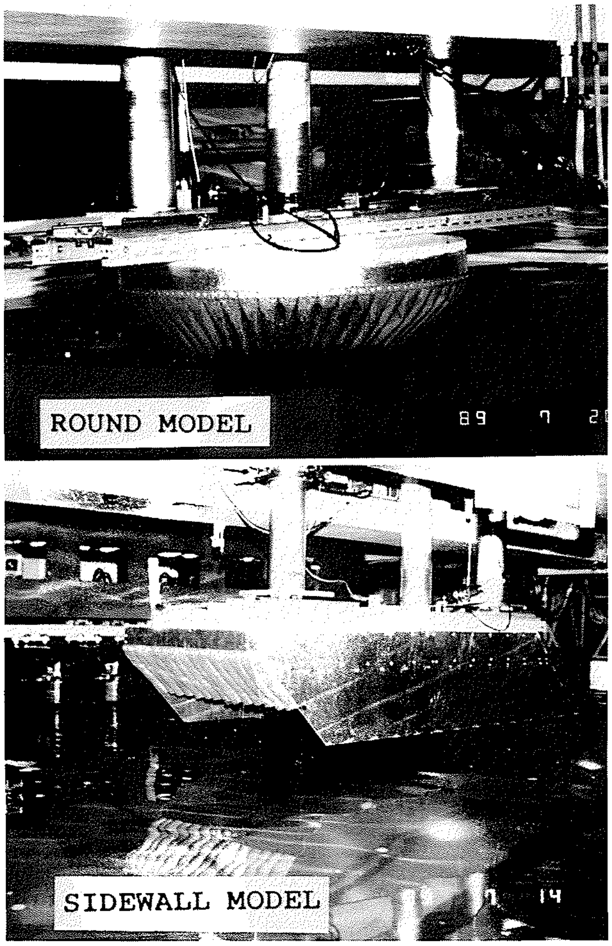
Experience with the icebreaker and ACT-100 combination led in the early eighties to the development of a new craft known as the air cushion icebreaker bow. This is shown in Fig. 2. It had a wedge section in its skirt to simplify mating with a host ship which in many cases was just a tugboat. This combination operated in the Thunder Bay port area during the spring of 1983 and 1984, where it broke ice about 1 m thick. One problem experienced by the Thunder Bay craft was skirt failure near the wedge section. In hindsight, it appears that adding a wedge was a backward step in development. Because of this, in 1984, two new craft with very simple skirt designs much less prone to failure were proposed (Colbourne et al. 1984). This paper describes scale model tests on these new designs and work on the high speed mode of icebreaking.

Low speed hovercraft icebreaking

Circular and sidewall concepts

As mentioned above, in 1984, two new craft were proposed. One was a circular or round planform craft designed for

Fig. 3. Pictures of air-cushion icebreaker bow models.



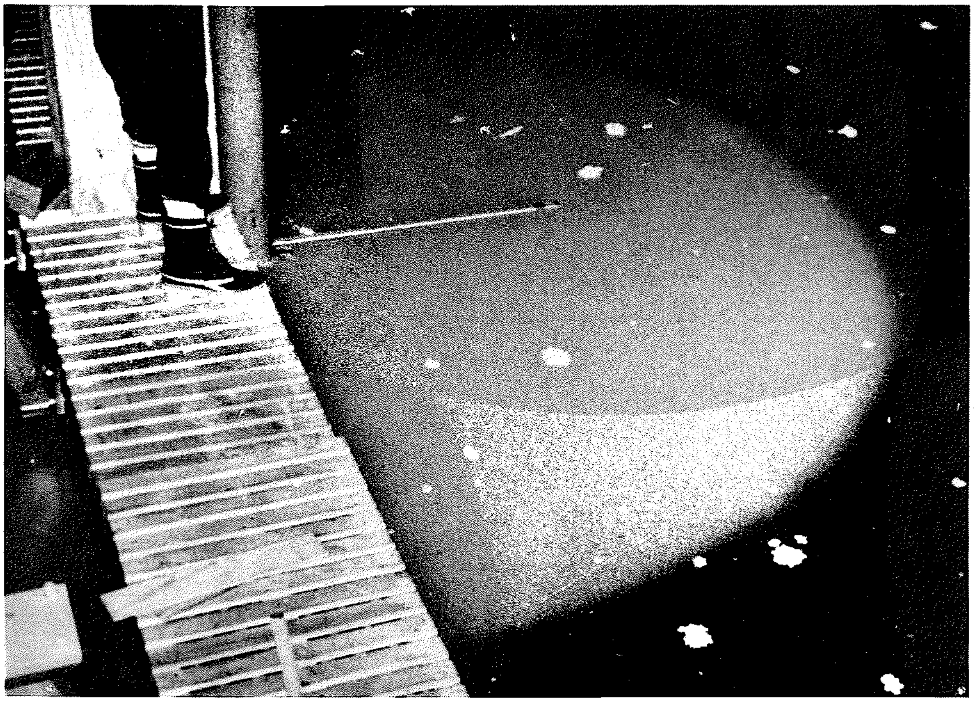
operation in inland waters with an ability to break uniform ice sheets about 1 m thick at full scale; the other was a sidewall craft designed for mid-Arctic operation in regions where ice sheets, with moderate ridging, are typically about 2 m thick. To improve steering control, the length of the sidewall craft was shorter than its beam. Both craft used a simple kneeless segment skirt to simplify maintenance. Both used drag sheets to keep the skirt free from ice blockage, and both used a spray apron to minimize spray-ice buildup on the superstructure.

Exploratory work at the Institute for Marine Dynamics

Models of the new craft were constructed at Memorial University of Newfoundland (MUN) at a geometric scale of 1:20 and tested in the ice tank at the Institute for Marine Dynamics (IMD) in Newfoundland. For this, the sidewall craft was first scaled down to the size of the round craft. Pictures of the models are shown in Fig. 3. Each had a support structure constructed from plywood approximately 18 mm thick and aluminum plate 3 mm thick. Each used a kneeless segment skirt made from a light nylon fabric approximately 0.25 mm thick supplied by United Sailworks (Newfoundland). Neither model used drag sheets or a spray apron. It was felt that these were unnecessary complications at model scale. It was also felt that a skirt at the rear of the sidewall craft was unnecessary; an inclined flat plate was used instead in the model. The sidewall craft used a total of 14 segments while the round craft used 60. The size of the segments was the same for each craft. For the tests, all model motions, except for surge, were suppressed. It was hoped that this would simplify data interpretation. Each model was towed over a number of sheets, each with a thickness that was approximately uniform throughout, at a number of constant speeds; its resistance to forward motion in each case was measured with a load cell. Cushion pressure and flow were also measured, and video cameras were used to record the icebreaking action. A vortex blower was used to supply cushion air. Standard procedures were used to grow ice sheets with scaled mechanical properties (Colbourne 1989).

Some preliminary tests with the round model on intact and prebroken sheets showed that the breaking component of resistance for this craft is insignificant, at least at low speed. This is not really surprising because the ice in the air cavity breaks under the action of its own weight. This suggests that, for round craft resistance scaling, ice properties such as strength have at best only a minor influence. Resistance to forward motion, F, can be nondimensionalized in a number of ways. In hydrodynamics, it is customary to nondimensionalize it by a force equal to a pressure times an area. This is the approach taken here. The dynamic head due to craft motion gives a pressure. However, for work on the air cushion icebreaker bow, the cushion pressure, P, is probably more appropriate and is used herein. For an area, one could use D^2, where D is the width of the cushion, which for both models tested at the Institute was approximately 0.91 m. This area is a measure of the cushion footprint and so PD^2 would be a measure of the craft weight. Resistance in this case would be given relative to the craft weight: $\mathrm{CF} = F/PD^2$. Now, to some extent, an air cushion icebreaker bow acts like a water plow with an area given approximately by HD, where $H = P/\rho_W g$ is the depth of the trough formed by hydrostatic pressure, ρ_W is the density of water, and g is the acceleration due to gravity. The cushion pressure acts over this area to give the force PHD. Resistance as a fraction of this force is $\mathrm{CF} = F/PHD$. The present data suggest that this is a better nondimensional representation of resistance. One could present the forward speed, U, nondimensionally as a Froude number: $\mathrm{CS} = U/\sqrt{gD}$. However, as mentioned earlier, during hovercraft operation, an air cavity or bubble is often seen beneath the ice sheet. Using the cavity propagation speed, U_b, instead to nondimensionalize U gives $\mathrm{CS} = U/U_b$. The present data suggest that this CS is more appropriate. In a study of cavity propagation, Hinchey (1989) found that it resembled that of a gravity or density current. Typically, this has a breaking head wave at its front. Benjamin (1968) showed for this, using a simple application of the steady Bernoulli equation, that $U_b = \sqrt{2gd(1-\varkappa)}$, where d is the depth of the cavity behind the front and $\varkappa$ indicates the position of a stagnation point on the front. Experiments show that $\varkappa$ is approximately 0.35 (Benjamin 1968). In the following, $\mathrm{CF} = F/PHD$ and $\mathrm{CS} = U/U_b$ are used. Figure 4 shows one of the cavity propagation setups used by Hinchey. Nondimensional representations of cushion pressure and flow were also developed. For cushion pressure, the thickness of ice corresponding to the cushion pressure was nondimensionalized by the sheet thickness itself ($\mathrm{CH} = P/\rho_I gh$, where ρ_I is the density of ice and h is the sheet thickness). The cushion

Fig. 4. Cavity propagation setup.

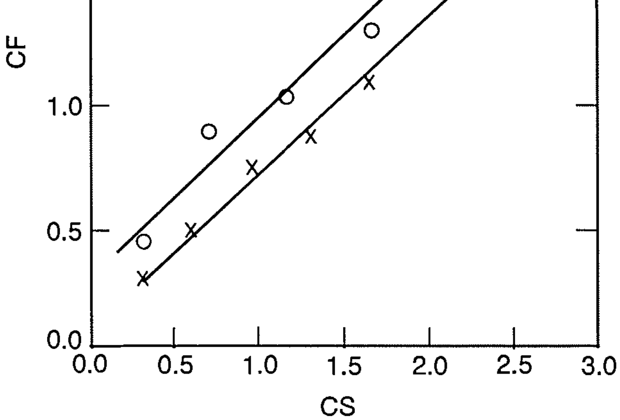


flow, Q, was nondimensionalized by the flow $Q_0 = U_0D^2$, where, from Bernoulli, $U_0 = \sqrt{2P/\rho_A}$ in which ρ_A is the density of air (CQ = Q/Q_0).

Figure 5 shows nondimensional resistance data for the round model generated during intact and prebroken sheet runs over a 40 mm thick sheet (0.8 m full scale). As mentioned previously, the close agreement suggests that the breaking component of resistance is insignificant. Surprisingly, the resistance curve for the prebroken sheet is slightly higher than the intact sheet curve. Observations of video records show that this is due, at least in part, to craft–ice contact caused by a vertical rotation of the broken ice pieces as they entered the cushion. Data also show that craft with larger CH generate a slightly larger CF. Video records show they also have greater ice breaking action and more craft–ice contact. The larger CF is probably caused by this. Recall that for a given sheet a larger CH implies a deeper and thus faster moving cavity beneath the sheet. Figure 6 shows that data obtained from intact sheets, each with a different thickness but with approximately the same CH, collapse approximately to the same line. In addition, it shows that the present data are in agreement with tank data obtained by ARCTEC (LeCourt and Kotras 1975) for a rectangular planform model having approximately the same CH and D. Note that the slope of the line in Fig. 6 is approximately unity. This indicates that the plow mechanism for resistance contains the essential physics.

Figure 7 gives data for the sidewall model. For the data denoted by the symbols ○ and ●, channels in the sheets for the sidewalls were precut so the resistance penalty due to the normal shearing action of each wall was not present. A comparison with the data denoted by the symbols × and * from sheets without channels shows that this resistance penalty is significant. However, it may be insignificant at full scale.

Fig. 5. Round model broken sheet resistance data.



For each intact sheet, the peak in total resistance near CS equal to unity suggests that CS is still a good representation of forward speed; however, CF itself is definitely inadequate.

A comparison of sidewall model data with that of the round model shows that resistance levels for both models are similar, provided the resistance penalty for the sidewall model is subtracted from its data and the CH values are approximately the same. For a given CH, because of its

Fig. 6. Round model intact sheet resistance data.

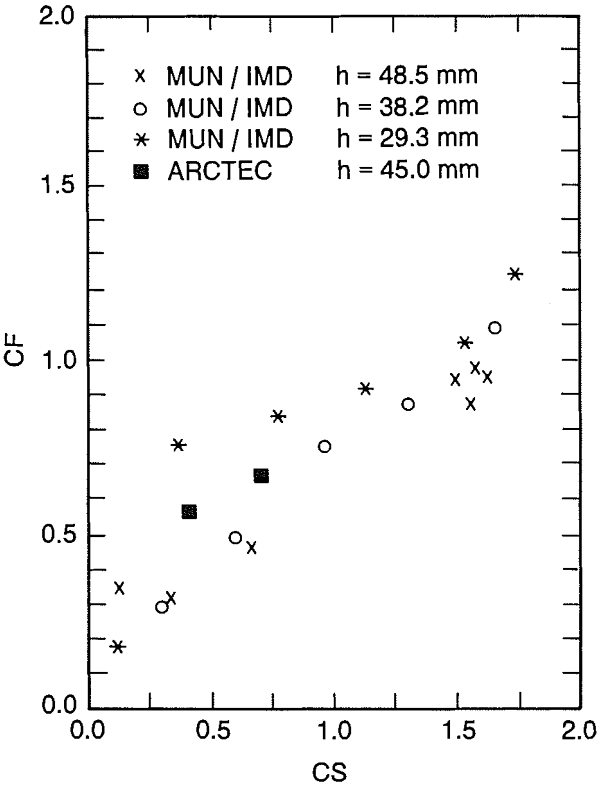
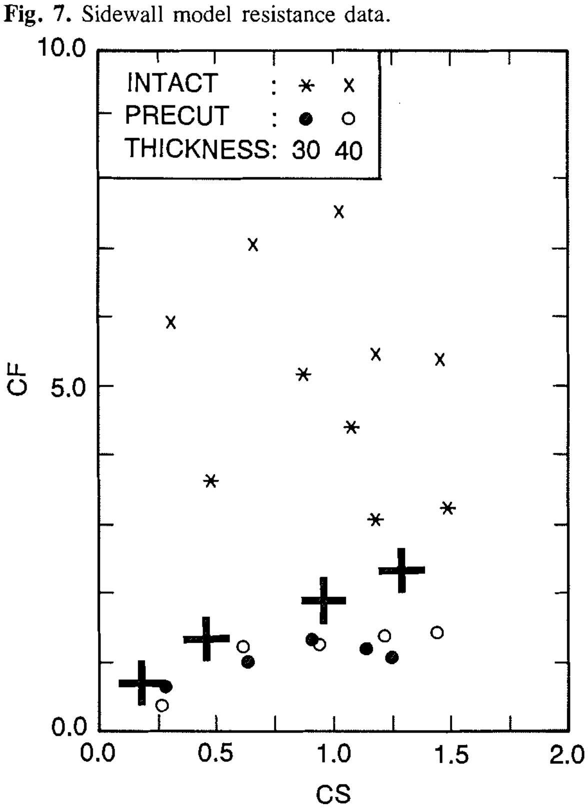
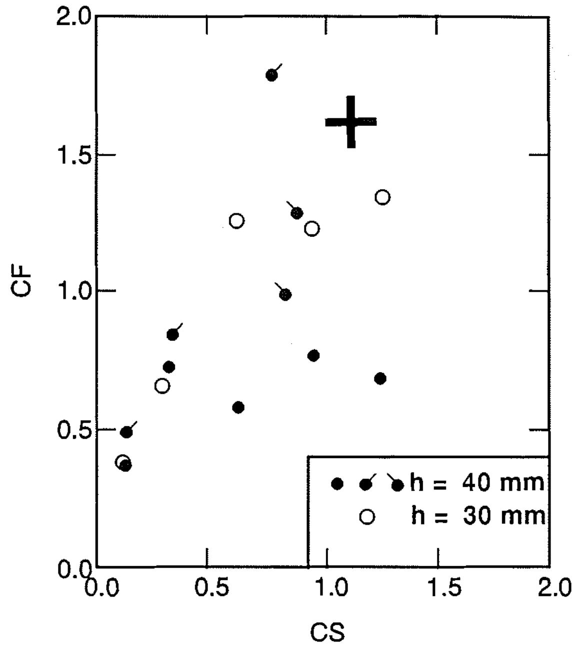


Fig. 7. Sidewall model resistance data.



smaller escape perimeter, CQ for the sidewall model was usually around half the CQ for the round model. This implies that the sidewall craft uses less power to generate its cushion: so the resistance penalty is counteracted to some extent.

Fig. 8. Intact sheet data for towed round model.



However, with aft skirts, this would not be the case.

It should be noted that the field CH needed to break ice is usually just above unity or much lower than that needed by tank models. ARCTEC observed a similar phenomenon in their tank data. This is probably due to the tank ice being much tougher or more flexible than field ice, partly because it has fewer imperfections. During operation of the round model at the field CH level, the ice could be seen to deflect such that an air cavity was not formed under the sheet, even when on the basis of CH it was to be expected.

Recent work at the Institute for Marine Dynamics

In recent tests, the round model was given greater freedom of movement. It was towed by a pretensioned wire which permitted considerable movement in heave, pitch and roll. Figure 8 shows resistance data for it obtained from intact sheets with different thicknesses but with model weight adjusted such that CH was approximately the same for each. As can be seen, the data contain significant scatter, but the scaling laws are still adequate. The video records show that for the low CF data points denoted by the symbol ● the icebreaking action was poor, mainly because the ice had not been tempered sufficiently. One data point denoted by the symbol + for the full-scale craft ICEATER-I pushed by the light icebreaker ALEXANDER HENRY is given in Fig. 8. Other data points show similar agreement with a unit slope CF−CS line but are outside the CF−CS bounds of Fig. 8. We also recently examined the performance of the round model in ice sheets with ridges. The propagation of the air cavity as it approached each ridge was recorded on video and the resistance during passage over the ridge was measured. It was found that only a few relatively high speed passages over a ridge were needed to break it down. Resistance was initially high but quickly fell to a low level. Obviously, more work in the IMD tank needs to be done to examine this in greater detail. Buoyancy chambers and aft skirts were recently added to a shortened version of the sidewall craft

Fig. 9. Picture of modified sidewall craft.

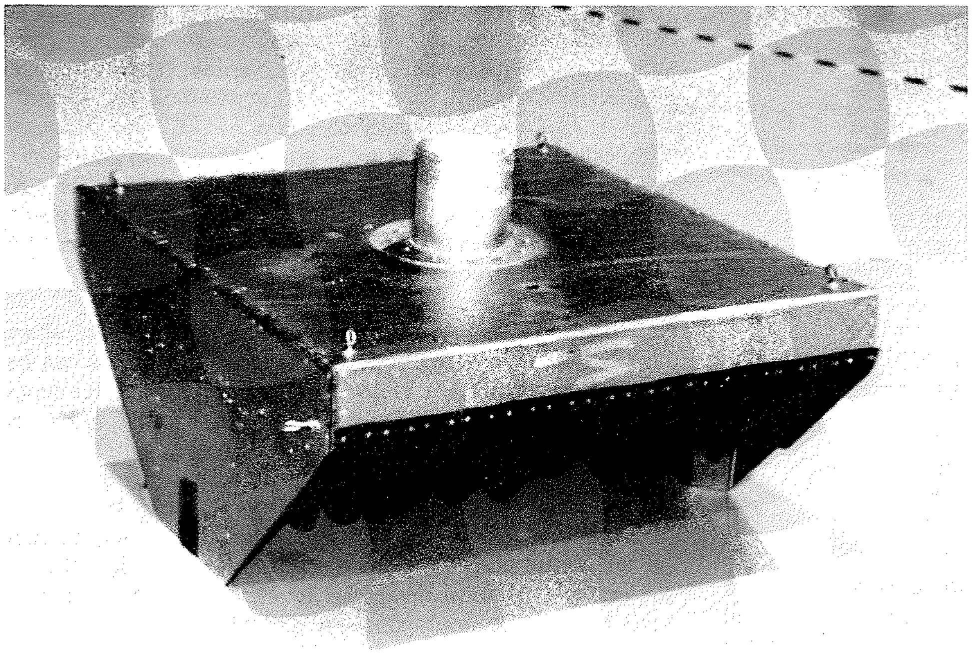
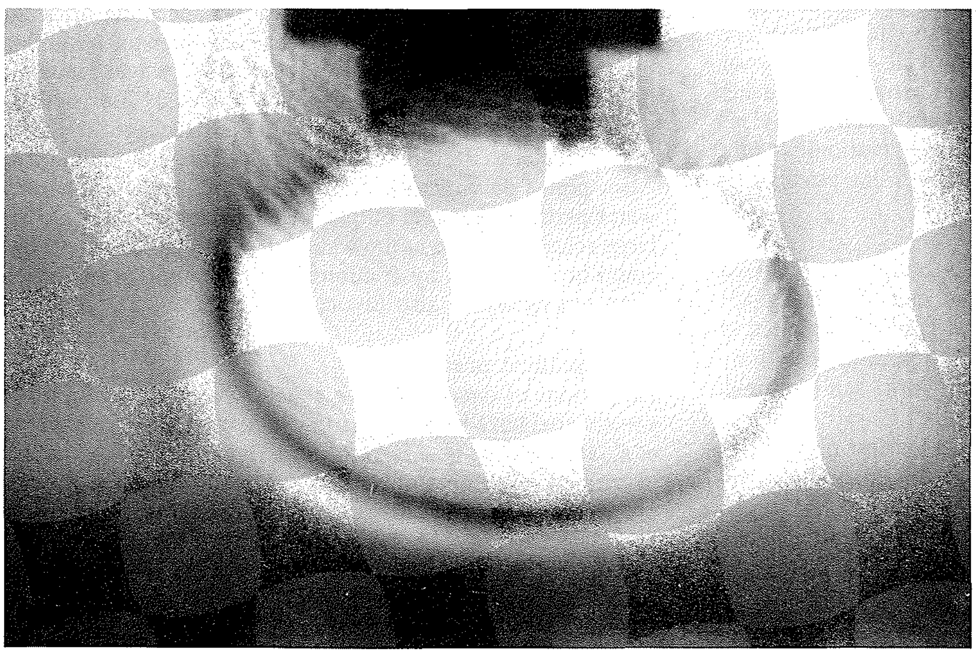


Fig. 10. Picture of suction bow icebreaker.

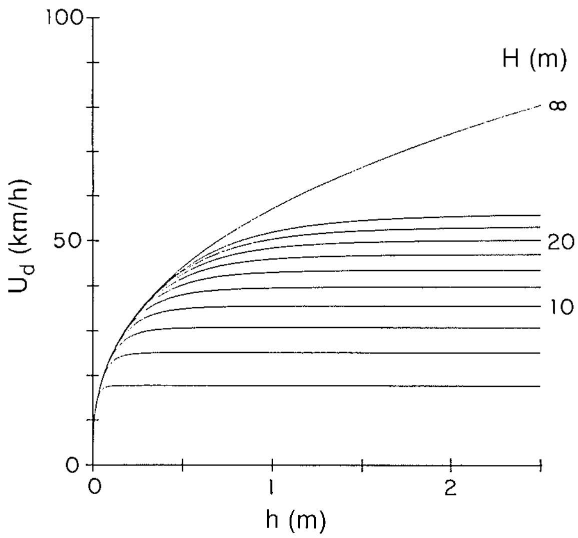


(Fig. 9). The buoyancy chambers allowed the craft to free float. Tow tests with it gave data close to that obtained with the original model; a few data points (+) for it from precut sheet runs are given in Fig. 7 (Hinchey and Colbourne 1992). Finally, we recently explored the possibility of using water pumps to suck water away from directly in front of a conventional icebreaker to improve its performance (Hinchey and Colbourne 1992). A pneumatic tube which acted like a skirt was used to isolate an area on the underside of a sheet (Fig. 10). A self-priming water pump was used to suck water from beneath this region and very good icebreaking action was observed which produced very small ice pieces. Note that if a perfect vacuum could be created beneath a sheet, it would be like having a 10 m column of water directly above it. In other words, the load on the sheet would be much more than just that from the weight of the overhanging sheet. In its present state, this concept would probably not work in practice; however, its very good icebreaking action suggests that its development should continue.

High speed hovercraft icebreaking

It has been known for some time that a critical speed exists for motion over a floating ice sheet (Eyre 1977; Beltaos 1981).

Fig. 11. Critical speed vs. sheet thickness.



At this speed, large amplitude flexural gravity waves are generated. We believe these waves are a source of high speed mode hovercraft icebreaking. We have been studying the critical speed phenomenon both theoretically and experimentally. At the theoretical level, we developed an energy trap explanation for it based on wave energy propagation concepts, and this is reviewed below. We have also studied the wave generation in the wave tank at Memorial University of Newfoundland and in the ice tank at the Institute for Marine Dynamics. Because the wave generation is extremely complex, we have tried to limit our work to date to generation in intact sheets. In real ice sheets, this is sometimes not possible.

Energy trap mechanism

The underlying ideas of the explanation for the critical speed phenomenon given here are not new and can be found in the texts by Lamb (1945) and Lighthill (1978). The explanation was reported on by Hinchey (1987). A similar explanation, developed independently of the present work, can be found in a paper by Davys et al. (1985).

We take the ice sheet to be a thin intact lossless plate floating on water. A dispersion analysis for this gives

$$C_p^2 = (Dk^4/\rho_W + g)\tanh(kH)/k[1 + \rho_I k/\rho_W \tanh(kH)]$$

where H is the water depth, C_p is the phase speed of the waves, k is the wave number (wavelength $\lambda = 2\pi/k$), D is the flexural rigidity of the sheet, ρ_I is the sheet density, ρ_W is the density of water, and g is the acceleration due to gravity. The plate flexural rigidity is

$$D = Eh^3/12(1 - \nu^2)$$

where E is the ice elastic modulus, ν is its Poisson's ratio, and h is the sheet thickness.

By plotting C_p versus k or λ, one finds that a minimum phase speed exists. This minimum is the critical speed. Because the deflection pattern generated by a load moves with it, anything moving at a steady speed, U, less than the minimum C_p cannot generate waves. A load moving at speeds greater than the minimum C_p does work on the ice sheet water system. This energy is normally carried away from the load by bow and stern waves. The work done is proportional to the local wave amplitude, A, whereas wave energy is proportional to $C_g A^2$, where C_g is the group speed. It turns out that at the critical speed, $C_g = C_p = U$; above the critical speed, $C_g > C_p$ for the bow waves and $C_g < C_p$ for the stern waves. As the critical speed is approached from above, the energy balance and the A^2 versus A dependence causes A to tend to ∞ as C_g tends to C_p; bow and stern wave energy becomes trapped in the load reference frame. Below the critical speed, the deflection pattern is basically bowl shaped, and the deflections are finite.

Figure 11 gives some plots of critical speed versus sheet thickness for ice with $E = 5$ GPa and $\nu = 0.3$. As can be seen, the critical speed is a strong function of the water depth and for each depth the shallow water phase speed, $\sqrt{gH}$, is its upper limit. It is also strictly a characteristic of the ice sheet water system and is independent of the characteristics of the load. The critical wavelength is typically two orders of magnitude greater than the sheet thickness. Thus, the thin plate model should be good even for very thick sheets. A thick sheet model developed by Hinchey (1987) supports this hypothesis. In practice, the deflections are finite at the critical speed. This is because of nonlinear phenomena and dissipation, both of which were ignored above. For an open water wave of a specific wavelength, an upper limit of wave height exists, beyond which the wave form becomes unstable and breaks down. This is a nonlinear phenomenon. A similar breakdown process could be expected for waves under a floating ice sheet. If it exists, it would obviously limit deflections at the critical speed. A diffraction-like leakage of energy perpendicular to the direction of motion is another possibility. Also, points on an ice sheet move mainly in heave whereas water particles move in elliptic orbits. Thus, there could be large relative motion at the water–ice interface, and energy could be dissipated by friction there. Finally, formation of sheet cracks would also dissipate energy.

Wave pattern predictions

Predictions of overhead wave patterns based on a thin plate sheet model have been reported by Hinchey (1987) and Davys et al. (1985). The details of the underlying theory will not be given here. We note only that it is based on wave energy propagation concepts. Typical patterns generated by it for a deep water case are shown in Fig. 12. For the lower speed, only two bow waves and two stern waves are shown; for the higher speed, the scale is smaller and only one of each is shown. In reality, there are an infinite number of waves ahead and behind. As can be seen, near the critical speed the bow and stern waves are almost planar. As speed increases, the bow wavelength becomes smaller and the stern wavelength grows. At speeds much greater than critical, the bow waves bend back sharply, and the stern waves take on a Kelvin-Wedge or open water character. The latter is not surprising because at high speeds the stern waves have a very long wavelength. Because of this, the flexural rigidity of the sheet has little effect and the waves are gravity dominated. Predictions for shallow water operation show that when the load speed is greater than the shallow water phase speed, $\sqrt{gH}$, a shadow zone without waves appears behind the load. Extensions of the wave energy theory are being developed,

Fig. 12. Wave pattern predictions.

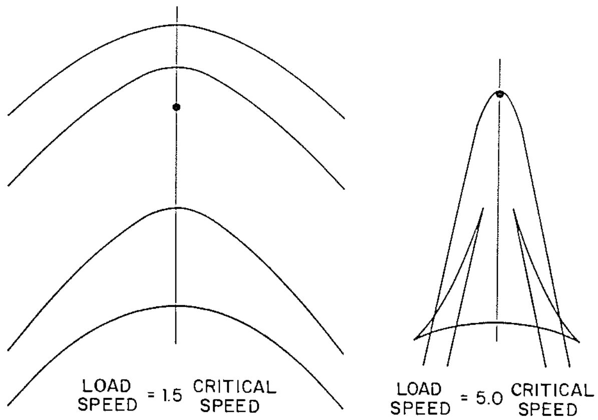
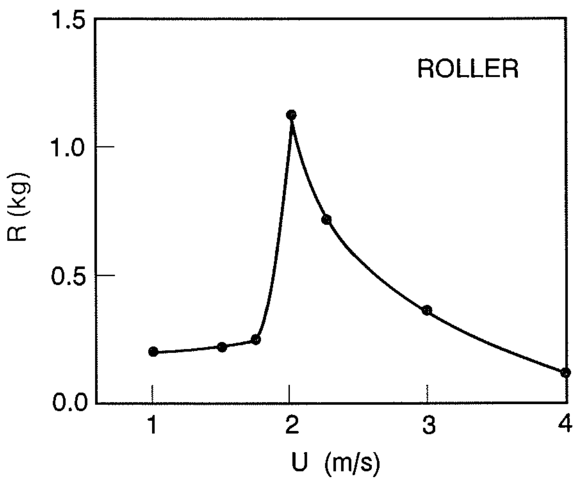


Fig. 13. Resistance data for roller load.



which give deflections not just patterns. This is complicated by uncertain dissipation and nonlinear phenomena.

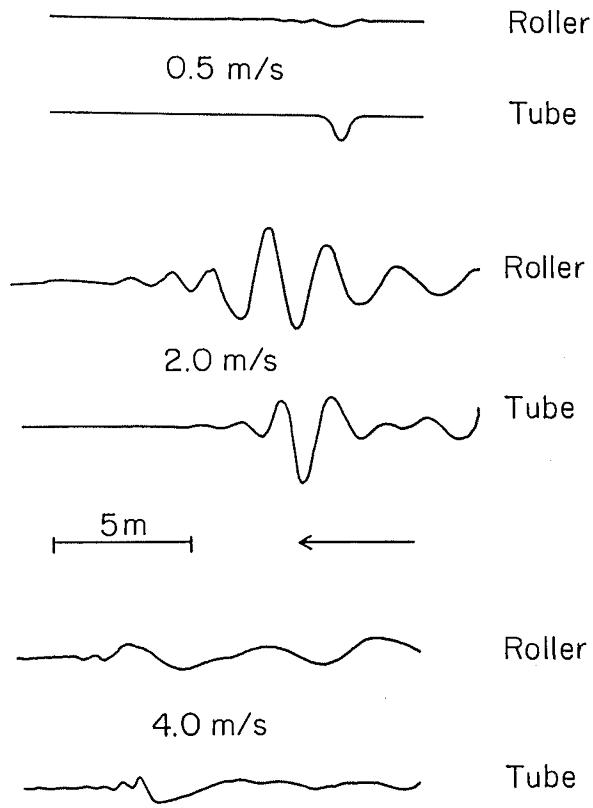
Styrofoam sheet experiment

This experiment was conducted in the wave tank at Memorial University of Newfoundland. A styrofoam sheet was used to simulate an ice sheet, and the deflection patterns generated by various loads towed over it were measured. The maximum test speed was 5 m/s.

Styrofoam sheet

The overall size of the sheet used was 30 m by 4.27 m. It was 3.18 cm thick. Ideally, to ensure uniformity throughout the sheet, it should consist of one continuous piece of styrofoam. Unfortunately, we could not purchase or make such a sheet. Instead, the sheet used was constructed by lap joining pieces of the maximum commercially available size of styrofoam, which is 4.27 m by 1.22 m. A construction technique was devised to reduce the effect of the discontinuities in the sheet caused by the joins. Each section of the sheet was constructed using two pieces of styrofoam, 4.27 m by 1.22 m by 1.59 cm, glued together to produce the total thickness of 3.18 cm. The two pieces were offset 15.24 cm before they were glued together so that sections could be lap joined. Since at every 1.22 m in the final sheet, there was a discontinuity where the sections of the sheet overlapped, we decided to add several cuts to the sheet in an orderly pattern in both directions. It was hoped that these would make the sheet approximate a uniform sheet. The cuts were 3/4 of the thickness of each layer and staggered in both directions. The distance between these cuts was 15.24 cm, i.e., the join offset. This is small compared with the expected wavelengths around the critical speed. Samples of the styrofoam sheet were prepared and tested in an INSTRON (tension/compression) machine. This gave a value of 13.4 MPa for the modulus of elasticity of styrofoam. With this, a static beam deflection test gave for the sheet an effective thickness of 2.60 cm. Using this information, the flexural rigidity of the sheet was determined, and the anticipated critical speed and wavelength were calculated to be 1.93 m/s and 1.79 m, respectively. Although the sheet was extremely fragile, repeat tests suggested that its characteristics were approximately constant during the test program.

Fig. 14. Roller and single tube deflection data.



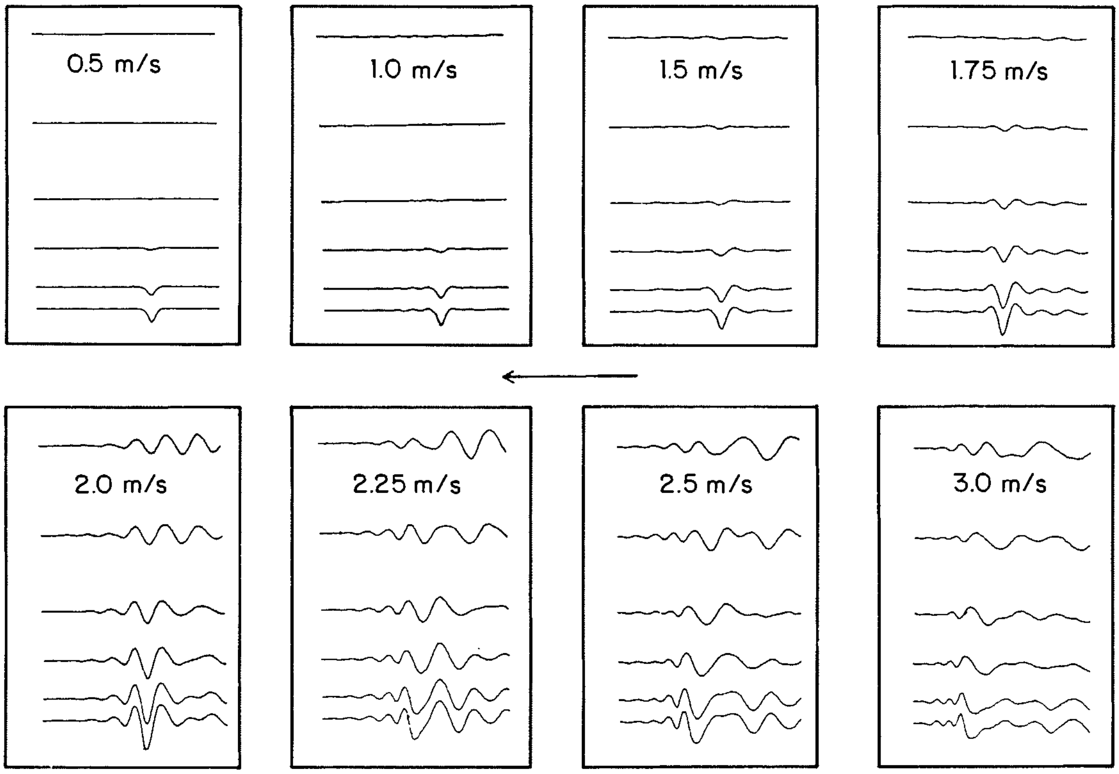
Instrumentation and loads

The sheet was instrumented with six deflection sensors. Deflection was sensed by lines attached to the sheet. These rode over pulleys attached to rotary potentiometers. A frame was fabricated, which connected the loads to the towing carriage of the tank. A load cell was incorporated into the frame. Pneumatic tubes and a roller which spanned close to the total width of the sheet were used to load the sheet.

Towing resistance data

Resistance data were obtained only for the roller load. The towing resistance for a test was taken to be the mean of the

Fig. 15. Cross sheet deflections: Single pneumatic tube.



data after the start up where the load accelerated up to the test speed. Figure 13 is a plot of resistance, R, versus speed, U. It shows that the critical speed is around 2 m/s. Recall that the anticipated critical speed based on thin plate theory is 1.93 m/s. Note how abruptly the resistance or drag increases as the critical speed is approached from below and how it gradually falls off above. The energy trap mechanism shows that this is to be expected. Below the critical speed, the load sits in a bowl-shaped depression which, relative to the load, is basically symmetrical fore and aft. Thus, as the load moves, it does essentially zero work on the ice sheet water system. Therefore, the drag is low. However, as the critical speed is approached from above, the wave steepness increases and the load rides on the back slope of a wave. Therefore, the work done and the drag both increase in this limit, but have upper levels determined by dissipation and nonlinear phenomena.

Deflection data

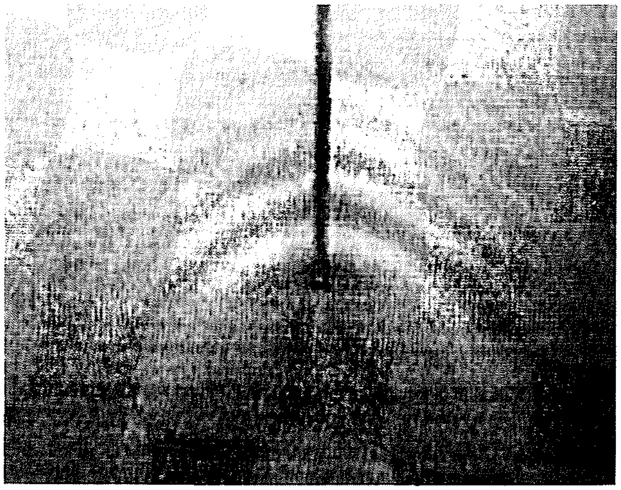
Some deflection versus distance traces generated by the roller and a single pneumatic tube load are shown in Fig. 14. Again, these show the critical speed to be around 2 m/s. Notice how at the lower speed the roller deflection is much less than that due to the pneumatic tube. This is to be expected because the roller load, although greater, is spread over a much larger area. Surprisingly, each load generates approximately the same maximum deflection. This suggests that some upper limit independent of the load has been reached. This in turn suggests that nonlinear phenomena are present. Note that the data in Fig. 14 suggest an upper limit on wave steepness below 0.1, which is somewhat less than the open water limit of 0.14. However, the sensor in each case was not directly beneath the load, so the upper limit may be higher. Deflections generated by a single pneumatic tube load are shown in Fig. 15. Note in Fig. 15 that, for speeds less than the critical speed, the deflection pattern is approximately bowl shaped and the shape of the bowl is speed dependent. As the speed approaches the critical speed, the bowl becomes deeper and spreads laterally; it appears that the bowl is trying to evolve into a planar wave. Most previous researchers had not seen this. However, recent field measurements by Takizawa (1988) confirm it. Its significance for icebreaking is not yet known. Note also in Fig. 15 that in most cases significant deflections occur at the side edges of the sheet. Therefore, comparisons with infinte sheet theory may be inappropriate.

Institute for Marine Dynamics tests

We also did resistance tests in the ice tank facility at the Institute for Marine Dynamics using a small pneumatic tube hovercraft model with cushion diameter of approximately 50 cm. The ice sheet was approximately 1 cm thick, and its critical speed based on thin plate theory was around 2 m/s. The resistance to weight ratio in this case was found to be approximately 0.06 maximum. When the roller resistance data for the styrofoam sheet are divided by weight, one finds that it gives approximately 0.05 maximum. This is quite close to a peak in the resistance to weight ratio found in ARCTEC tank data (LeCourt and Kotras 1975). So, we have three quite different experiments giving approximately the same result. This again suggests that nonlinear phenomena are important. This is probably the most significant outcome of our work.

Tests with an air jet load, instead of the hovercraft model, showed a transition from a bowl-shaped depression to a

Fig. 16. Wave pattern in nylon fabric sheet.



system of bow and stern waves near 2 m/s. Unfortunately, in the time allotted, we were unable to get any high quality photographs or videos of this.

Plastic sheet tests

To obtain some wave pattern data at a scale where observation is easier, a series of exploratory tests were carried out on a 0.3 mm polyethylene plastic sheet. Polyethylene has an elastic modulus around 172 MPa. The critical speed based on this and the sheet thickness is 0.50 m/s. This means that, in the MUN wave tank, speeds 10 times greater than the critical speed are possible in this case. The sheet tested was 1.37 m by 9.5 m. It was draped over a wooden frame with inside dimensions 1.22 m by 9.1 m. It was permitted to lay on the water, and it was stapled to the frame to keep its edges out of the water. An air jet was used to load the sheet, and patterns generated were recorded photographically. As expected, the transition from a bowl-shaped depression to a system of bow and stern waves occurred near 0.5 m/s and the waves closely resembled those seen in the IMD tests. One problem with the plastic sheet setup was the sheet was very prone to wrinkle, especially when it came into contact with cold water. Therefore, the quality of most photographs was not good.

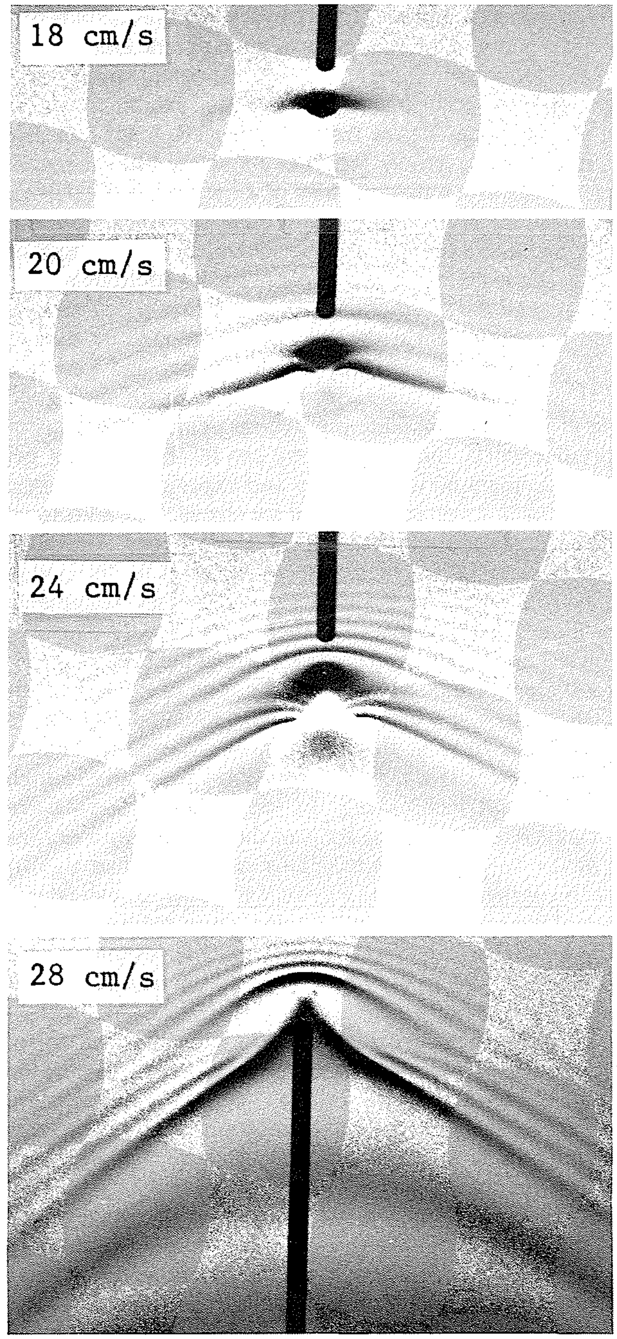
Fabric sheet tests

In an attempt to get around the wrinkle problem of the plastic sheets, various fabric sheets were tested. Only one showed any promise and this was a waterproof 0.5 mm nylon sheet supplied by United Sailworks (Newfoundland). During tests on it we observed the transition from a bowl-shaped depression to a system of bow and stern waves. Figure 16 shows a photograph of a typical wave pattern generated in the sheet by a 10 mm air jet load. The quality of this is not good because it was taken from a video record.

Membrane sheet tests

Some tests were conducted in the wave tank at Memorial University of Newfoundland using a small air jet load over open water. Here, the surface tension at the air – water interface acts like a membrane. Theory shows that this acts very much like a thin plate. It has a critical speed around 20 cm/s. Wave pattern predictions for it can be found in the hydrodynamics text by Lamb (1945) and these are surprisingly similar to those presented earlier for a thin plate. After many attempts, some excellent photographs of the deflections of this membrane were obtained. Several of these are shown in Fig. 17. Note that similar patterns can be seen near a fishing line in a stream, which is why back in the 1800s, people like Lord Kelvin who worked on the problem referred to it as the fishing line problem.

Fig. 17. Membrane sheet deflection patterns.



Discussion and conclusions

To study the deflection patterns generated by high speed motion over an intact ice sheet, we used membrane and thin plate sheets. Surface tension at an air−water interface was used to mimic a membrane. Obviously, there are fundamental differences between the stretching of a membrane and bending of a plate. However, there are also fundamental similarities. Both membrane and plate floating sheets exhibit a critical speed phenomenon. Below the critical speed, loads generate little, if any, wave action, whereas above the critical speed, they generate a complex system of bow and stern waves. Because of the scale of the membrane or surface tension waves, they are easier to observe. Also, the membrane or surface tension sheet is always intact. So, it should be a good testing ground for predictions. We feel that much can be learned from thin fabric sheets. Like membrane or surface tension sheets, they generally remain intact and generate deflections at a small scale. So, they should provide a good testing ground for thin plate predictions. This is the focus of our present work. Basically, as we see it, if we cannot get a good agreement between theory and experiment for fabric sheets, we will never get it for real ice sheets. Our styrofoam sheet tests tend to support the critical speed theory. They also suggest that nonlinear phenomena as opposed to dissipation limit the amplitudes at the critical speed. They suggest an upper limit in wave steepness there around 0.1. The dispersion relationship gives the wavelength at the critical speed. With wavelength and steepness known, one can quickly estimate the stresses in a sheet and thus the potential for failure.

Recent tow tests at the Institute for Marine Dynamics showed that there is a complex transition from low to high speed hovercraft icebreaking. In some runs, a stern wave was observed where, on the basis of the energy trap mechanism, waves were not expected. This stern wave had significant icebreaking action. Its source is unknown. It may be just the rim of the bowl predicted by intact sheet theory. It could also be related to the formation of the hydrostatic trough directly beneath the craft. The water so displaced shows up, because of the intact sheet in front and to the sides, mainly at the stern where the sheet is weak or there is basically open water. We plan more tank tests at the Institute to examine the transition in greater detail. For the work, we hope to use digital image analyzers to get from photographic negatives three-dimensional views of deflection patterns. We also plan more tests on sheets with ridges.

Another area requiring attention is high speed shore approach, because the energy in the bow wave system may have a tendency to pile up in front. Dissipation and nonlinear phenomena could make such a pile up insignificant. We plan to use fabric sheets in the MUN tank and thin sheets in the IMD tank to check for it.

Finally, the air cushion icebreaker bow, which operated in the Thunder Bay port area, did not continue operation beyond 1984. In fact, it was sold soon after for scrap. Development up to that point had been funded by the Transportation Development Centre of Transport Canada and the Canadian Coast Guard. Soon after, funding was withdrawn and development effectively ceased. The same occurred for the high speed case. However, we feel both technologies are basically sound and we expect development to resume at some point in time.

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