

[54] ICEBREAKING

[75] Inventor: Edward O. Anders, Houston, Tex.

[73] Assignee: Global Marine, Inc., Los Angeles, Calif.

[22] Filed: Sept. 24, 1971

[21] Appl. No.: 183,466

[52] U.S. Cl. 114/40

[51] Int. Cl. B63b 35/10

[58] Field of Search 114/40-42,
114/16 E, 125, .5 D

[56]

References Cited

UNITED STATES PATENTS

993,440	4/1911	Duplessis	114/41
1,071,735	9/1913	Haagenson	114/40
2,066,150	12/1936	Hort	114/125
2,117,003	5/1938	Hasselmann	114/16 E
2,902,964	9/1959	Waas et al.	114/125
2,995,103	8/1961	Waas et al.	114/40
3,349,740	10/1967	Field	114/125
3,366,087	1/1968	Hilliard	114/125
3,521,591	7/1970	Alexander	114/41
3,636,904	1/1972	Blanchet	114/41
3,648,635	3/1972	Hashemi	114/40
3,660,856	5/1972	Smulders	9/8 P
3,689,953	9/1972	Markakis	114/125
3,690,281	9/1972	Gray	114/41
3,695,048	10/1972	Dimick	114/16 E

FOREIGN PATENTS OR APPLICATIONS

74,067	9/1953	Netherlands	114/41
458,616	12/1936	England	114/125

380,051	9/1932	England	114/125
561,379	9/1932	Germany	114/125
181,313	4/1904	Germany	114/41

Primary Examiner—George E. A. Halvosa

Assistant Examiner—Galen L. Barefoot

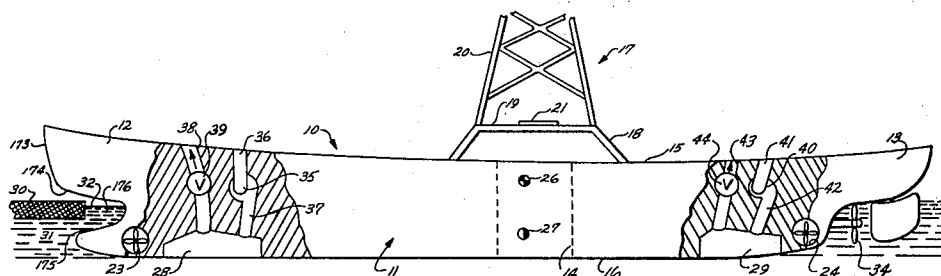
Attorney, Agent, or Firm—Christie, Parker & Hale

[57]

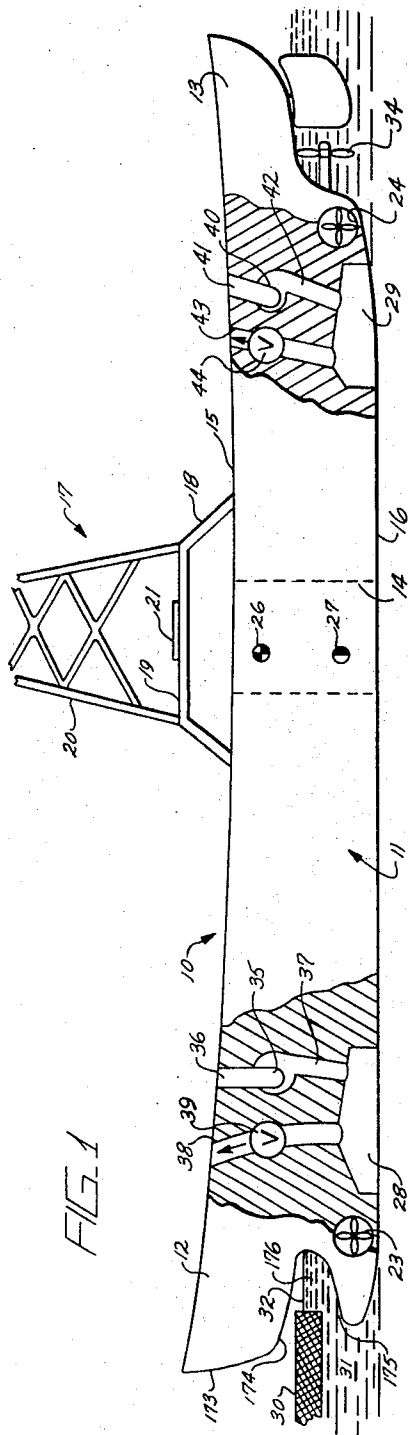
ABSTRACT

An icebreaking vessel includes pneumatically activated means adjacent at least the bow for altering the effective configuration of the submerged portions of the hull to produce a longitudinal shift in the hull center of buoyancy to induce a pitching movement of the hull. The pitch-inducing means is operated at a selectable frequency which is correlated to the optimum pitch energy transfer characteristic existing between the hull and its proximate surroundings, which surroundings may include an ice sheet and broken ice between the hull and the ice sheet. In most instances, the period of pitching approximates the natural pitch period of the hull in such surroundings. The bow may be configured to effectively engage and transfer force to an ice sheet during both upward and downward pitching movements of the bow. Also, portions of the hull along the forward surfaces subject to variable immersion in response to induced pitching of the vessel may be heated to prevent broken ice from adhering to the hull. Preferably, water expelled from the induced pitching mechanism is directed to drive broken ice adjacent the hull away from the hull.

31 Claims, 22 Drawing Figures



3,850.125



FILE 1

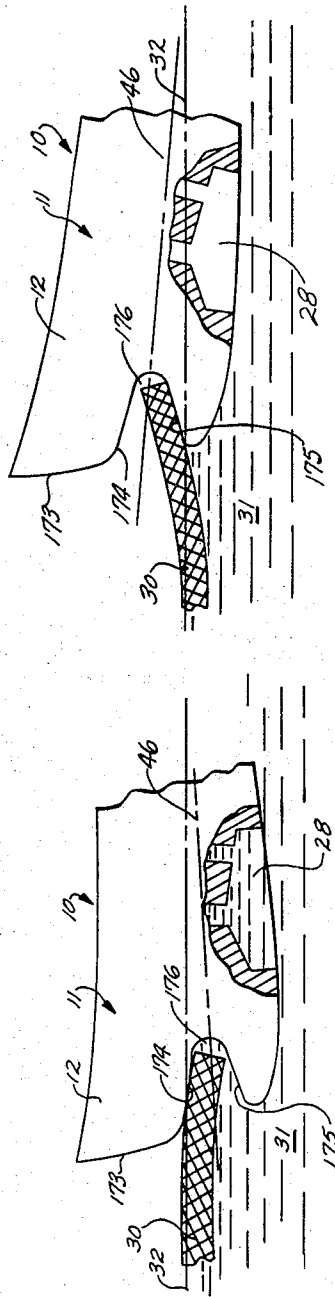


FIG. 12

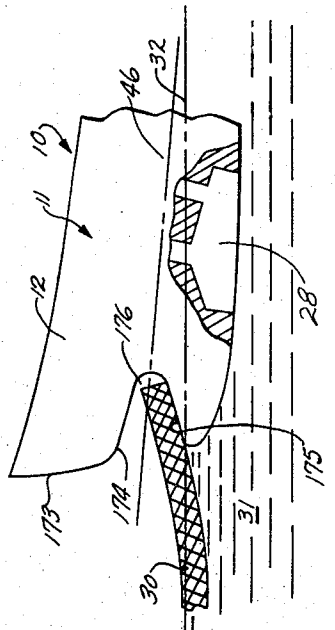
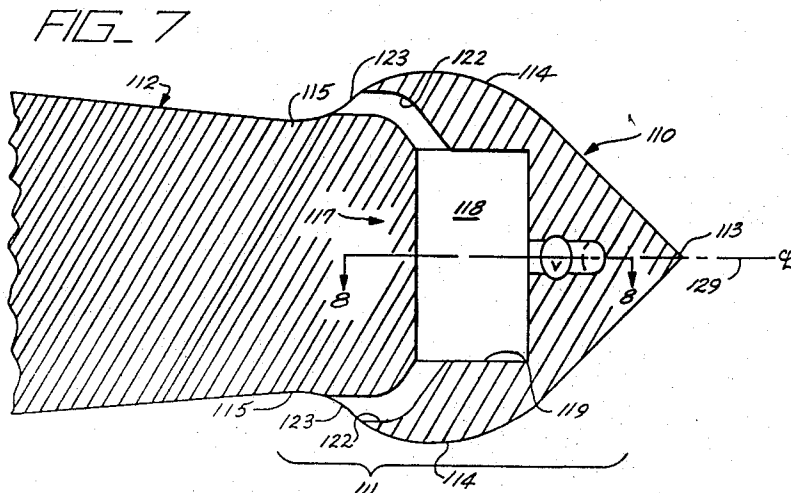
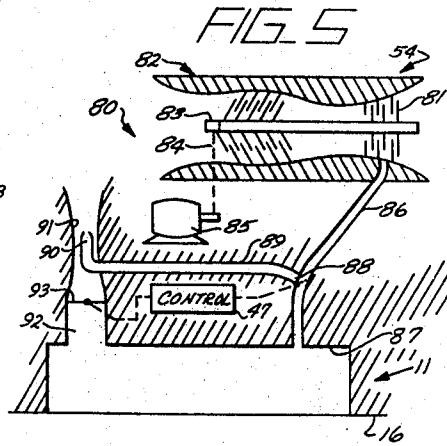
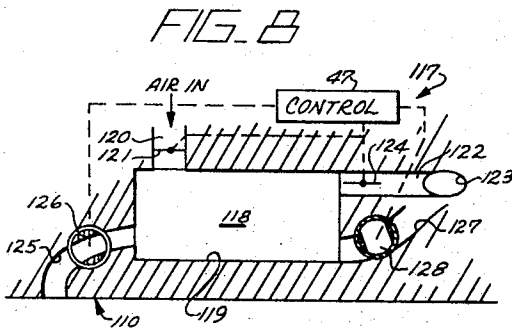
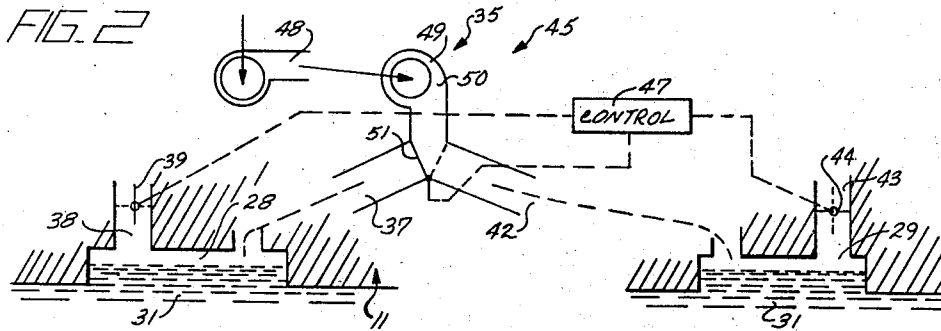
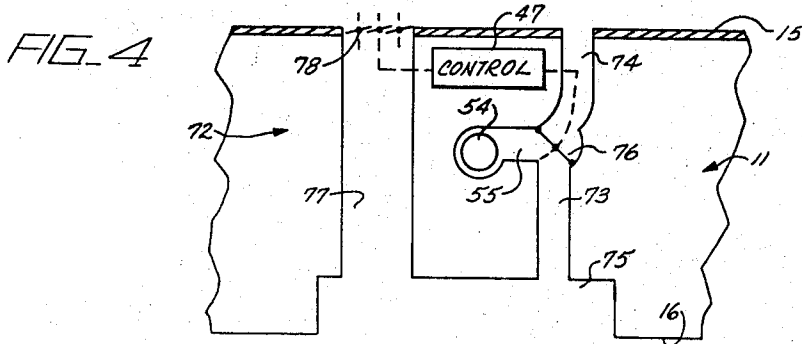
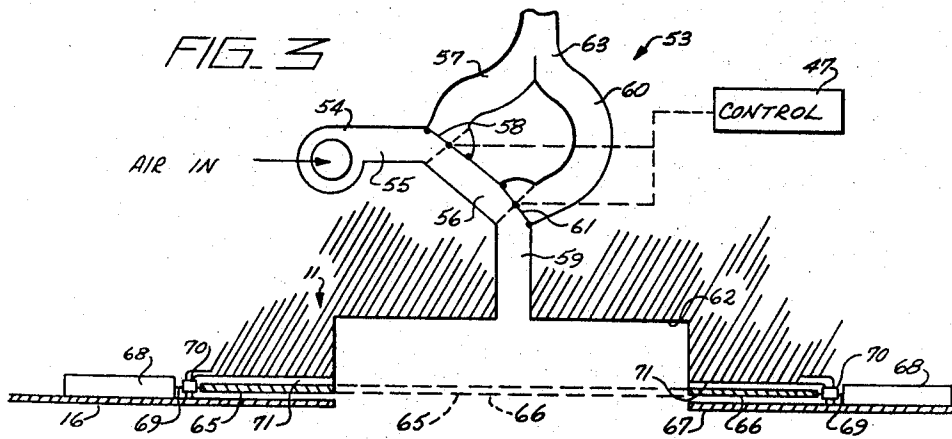
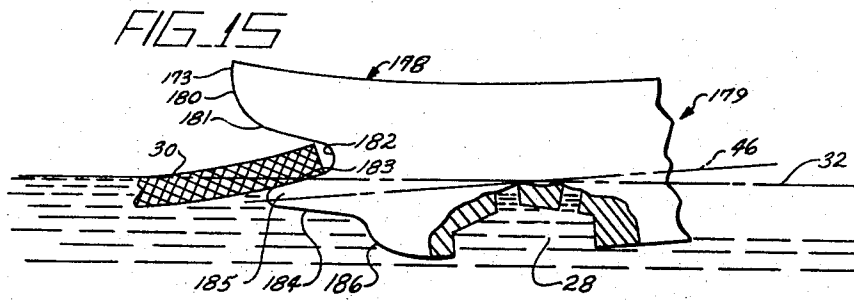
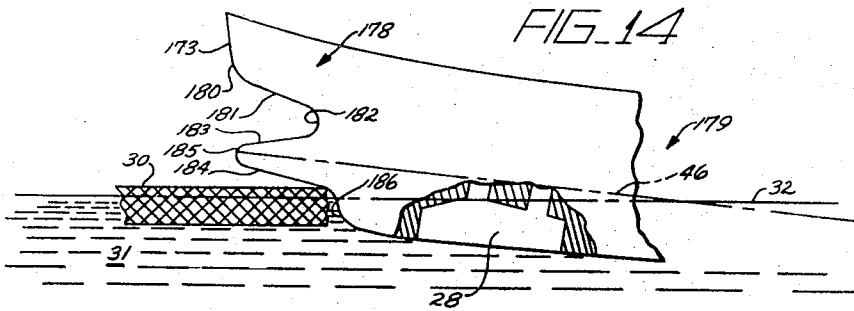
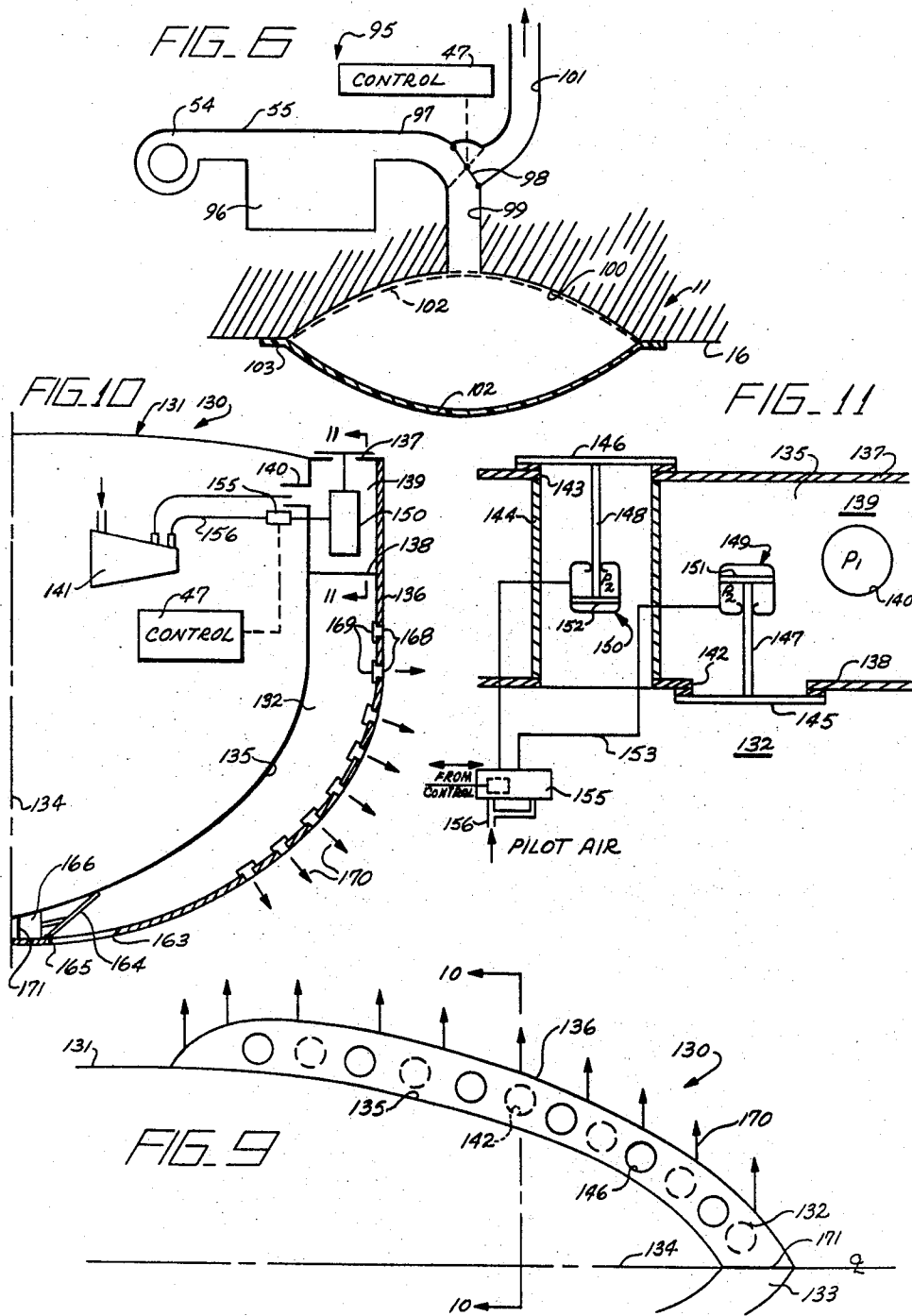


FIG. 12







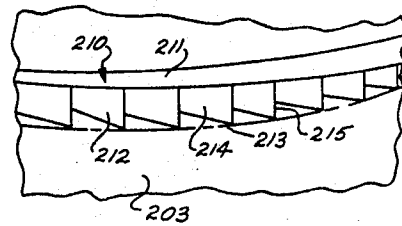
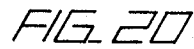
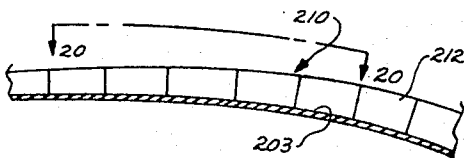
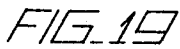
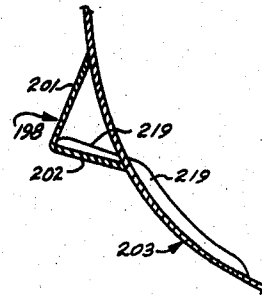
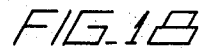
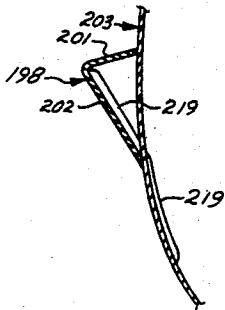
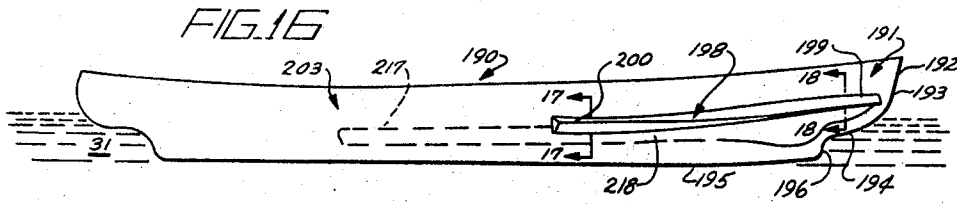


FIG. 21

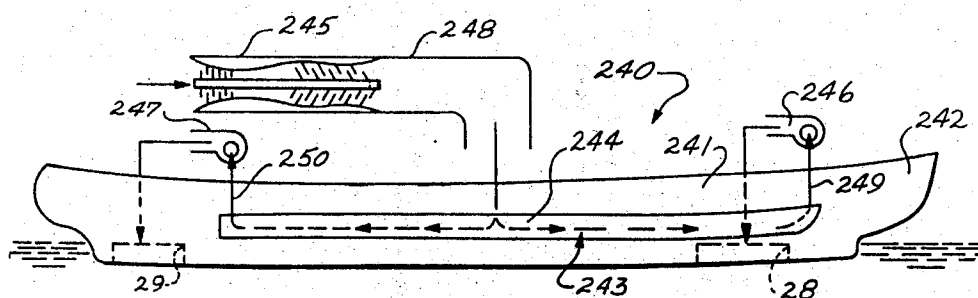
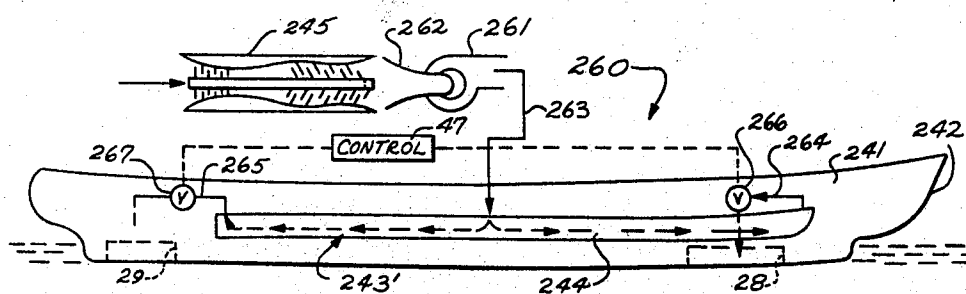


FIG. 22



ICEBREAKING

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention pertains to icebreaking ships. More particularly, it pertains to an improved icebreaking vessel equipped with a pneumatically biased pitch-inducing means operated in approximate resonance to the natural pitch frequency of the hull considered as a component of an overall system which also includes an ice sheet adjacent the hull and broken ice between the hull and the ice sheet.

2. Review of the Prior art

Icebreakers, from the time they originated many years ago with or shortly after the advent of steam propulsion for ships, until only very recently, have operated on the principle of brute force applied to the ice to be broken. Thus, traditionally icebreakers break ice either by plowing continuously through the ice sheet relying on the downward force applied by specially configured, highly raked bow structures to break the ice, or by a technique known as "boxing" or "ramming." In boxing, an icebreaker runs its bow onto an ice sheet too thick to be broken by continuous plowing until the ship breaks through the ice at about which time the ship is either at rest in the ice or nearly so; after the ice is at least principally broken, the icebreaker is backed off the ice into the track of broken ice until it is clear of the ice sheet, and then it is accelerated to once again ram into and ride up onto the ice. Boxing is effective to break ice substantially thicker than may be broken by continuous plowing through the ice at low velocity, but results in a much lower net advance rate of the icebreaker through the ice.

Conventional icebreakers rely upon the mass of the vessel to accomplish breakage of the ice during both continuous and boxing modes of operation. The forward end of an icebreaker may be ballasted to increase the effective portion of the overall mass of the vessel applied to the ice sheet, especially where the vessel becomes stuck on the ice during boxing of very thick ice sheets; this situation occurs where the momentum developed by the vessel approaching the ice carries the bow so far up onto the ice that the vessel is, in effect, beached on the ice.

Historically, then, the effectiveness of an icebreaker, measured in terms of the thickness of ice capable of being broken during boxing mode operation, has been determined primarily by the displacement (total weight) of the vessel and by the efficiency with which the specially configured bows of these vessels transferred forward momentum and weight of the vessel downwardly to the ice. The basic objective has been to apply sufficient force downwardly to the ice to cause the ice to break into pieces and to separate from the ice sheet. The upwardly acting icebreaker bow structures previously proposed or used, such as that described by Lunsingh in Dutch Pat. No. 74,067, are merely the opposite side of the coin to the conventional approach described above.

Not too strangely, the ratio of propulsive horsepower to displacement in icebreakers traditionally has been rather limited considering the task expected of such vessels. Propulsive horsepower has been limited to prevent the vessel from being driven so far up onto a thick ice sheet during boxing mode operation that the vessel cannot be backed off the ice, even when ballast is

shifted in the hull. Bows for icebreakers also are designed to limit hull advance onto an ice sheet to the point where the vessel can be backed off if beached.

Waas, Ehlers and Grim, in U.S. Pat. No. 2,902,964 (which issued in 1959 on an application based on a West German priority date of Mar. 13, 1953), described a group of icebreakers in which weight was transferred cyclically in the vessel to induce pitching and other movements of the hull purportedly in resonance with the corresponding natural periods of the vessel in such movements. The patent describes the use of counterrotating eccentric weights in the vessel, and the shifting of water ballast fore and aft in the vessel, and comment is also made that water can be pumped into and out of the vessel, all to pitch the vessel purportedly in resonance with the natural period of the hull.

In 1958, however, Waas presented a technical paper in West Germany which set forth a historical review of experience obtained up to that time with icebreakers equipped with mechanisms for inducing pitching and other motions in the vessel. The paper is "The Effect of Pitching Plants on Icebreakers," dated Sept. 17, 1958 at Bonn and presented before Schiffbautechnische Gesellschaft in November, 1958. The paper comments upon the experience of the West Germans and others with some ten or so icebreakers all of which were equipped with rotating weight systems operated to produce cyclic induced motion of the vessel at a frequency of 30 cycles per minute and preferably much greater. Waas then stated that induced pitch experience at these frequencies by such mechanisms had increased the icebreaking efficiency of the pertinent vessels. In one case, when the induced motion system was operated, the bow of the vessel experienced vertical excursions of 10 cm. (total amplitude) at the rate of 30 times a minute.

It is highly significant that the induced motion frequencies preferred by Waas in 1958 far exceed the natural motion frequencies of any vessel having the sizes and configurations discussed by Waas. The frequencies preferred by Waas in 1958 as effective had no relation whatever to the natural resonance frequencies of the hulls in question, and Waas suggested that much higher frequencies (on the order of 120 cycles per minute) of induced motion would be even more effective. It is also highly significant that the induced pitching motions described by Waas are of small amplitude. This practical experience and the suggestions based upon it are inconsistent with U.S. Pat. No. 2,902,964 with respect to hull resonance periods and, in effect, repudiate the patent as to its teachings concerning induced pitching motion of an icebreaker in resonance with the natural pitching period of the hull.

It is known that the United States Coast Guard has investigated the use of the high frequency techniques and mechanisms reported by Waas in 1958, but has not seriously pursued the matter of inducing pitch at natural frequencies in an icebreaker. It is also known that the Russians too have had experience with rotating weight pitching devices on small icebreakers.

In summary, then, prior practical experience with induced hull movements for icebreakers involved high frequency, low amplitude movements resulting from effects internal to the hull.

Even more recently, Waas stated that ballast systems, while effective to produce pitch in a ship under static

conditions, cannot be used effectively to produce forces with sufficient rapidity to attain something of a ship's natural rhythm of pitch; see "Icebreakers with Pitching Equipment," Dipl.-Ing. Heinrich Waas, *VDI Zeitschrift*, Vol. 101, No. 32, Nov. 11, 1959, pp. 1499-1502, Bureau of Ships Translation No. 699.

In a different area pertaining to icebreakers, attempts have been made to reliably predict the areas in which energy is expended by an icebreaker operating during both continuous and boxing modes. The most recent and most comprehensive predictions in this area are set forth in "Methods for Predicting Icebreaking and Ice Resistance Characteristics of Icebreakers," by J. W. Lewis and R. Y. Edwards, 1970 *Transactions*, page 213 et seq., Society of Naval Architects and Marine Engineers, New York, and particularly in equations (7) and (10) thereof. It has been estimated that of the total energy expended by an icebreaker in breaking ice, 5 percent of the energy is consumed in actually breaking the ice, 80 percent is consumed in moving the ice out of the way of the vessel and in overcoming the buoyancy of the ice, and 15 percent is consumed in overcoming conventional hull resistance; see Lewis and Edwards, supra, FIG. 13 at page 231.

SUMMARY OF THE INVENTION

This invention provides an economical, effective and efficient icebreaker which includes a pneumatically biased pitch-inducing system which operates in approximate synchronism with the natural pitch frequency of the vessel considered with regard to the frequency modulating effects of an adjacent ice sheet and of broken ice between the ice sheet and the vessel. Pitching is induced by effectively shifting the center of buoyancy of the vessel, rather than by shifting mass within the vessel as described by Waas et al. The present icebreaker is efficient in terms of required pitching horsepower because it relies upon the natural dynamic properties of the vessel to accomplish a significant portion of the buoyancy shifting, whereas prior pitch-inducing systems had to work against the dynamic properties of the vessel.

The present icebreaker differs from prior pitching icebreakers by providing low frequency, high amplitude movements of the bow. These high amplitude ship movements involve movement of substantial volumes of water, and water movement is controlled directly and indirectly to assist in moving ice out of the way of the hull in a track formed through an ice sheet. As a result, the present icebreaker is able to exert a greater portion of the available power to the ice to be broken and to effectively break greater thicknesses of ice faster than has previously been possible. The present icebreaker operates to more efficiently move ice out of the way of the vessel, thereby significantly reducing what is now the major drain of energy available from the icebreaker.

Also, the bow of the present icebreaker is arranged to apply pitching and forward momentum of the vessel to the ice sheet during both upward and downward movements of the bow; prior icebreakers operated to apply force only downwardly or upwardly to an ice sheet.

In its broadest aspects, this invention provides an improved vessel for use in ice-covered waters and includes a hull having a bow portion of icebreaking configuration. The vessel also includes means operatively

associated with the hull and at least principally pneumatically operated for shifting the hull center of buoyancy fore and aft at a selectable frequency. This frequency is within a range of frequencies each of which has a period measured in terms of several seconds. The buoyancy shifting means is operable to shift the center of buoyancy at the selected frequency without significantly altering the location of the center of gravity of the vessel. Operation of the buoyancy shifting means produces cyclic pitching motions of the hull, which motions have a period measured in terms of several seconds and an amplitude of at least a foot.

DESCRIPTION OF THE DRAWINGS

The above-mentioned and other features of this invention are more fully set forth in the following detailed description of certain presently preferred embodiments thereof which are illustrated in the accompanying drawings wherein:

FIG. 1 is a side elevation view, partially in cross-section, of an improved icebreaker and shows, in simplified form, a pitch-inducing mechanism according to this invention;

FIG. 2 is a schematic diagram of another pitch-inducing mechanism provided in the vessel shown in FIG. 1;

FIG. 3 is a schematic diagram of another mechanism for inducing pitching movements in an icebreaker according to this invention;

FIG. 4 is a schematic diagram of another pitch-inducing mechanism;

FIG. 5 is a schematic diagram of still another pitch-inducing mechanism;

FIG. 6 is a schematic diagram of another pitch-inducing mechanism;

FIG. 7 is a simplified top plan view of the bow portion of a different icebreaking vessel according to this invention equipped with still another pitch-inducing mechanism;

FIG. 8 is a cross-sectional elevation view taken along line 8-8 in FIG. 7;

FIG. 9 is a simplified top plan view taken at about the load waterline of the forward portion of another icebreaker according to this invention;

FIG. 10 is a simplified illustration taken along lines 10-10 in FIG. 9;

FIG. 11 is an enlarged cross-section view taken along line 11-11 in FIG. 10;

FIG. 12 is a fragmentary elevation view, partially in cross-section, of the icebreaker of FIG. 1 pitched downwardly during icebreaking operations;

FIG. 13 is similar to that of FIG. 12 showing the icebreaker pitched upwardly during icebreaking operations;

FIG. 14 is a fragmentary elevation view, partially in cross-section, of the forward portion of another icebreaker according to this invention pitched upwardly during icebreaking operations;

FIG. 15 is a view similar to that of FIG. 14 showing the icebreaker of FIG. 14 pitched downwardly in icebreaking operations;

FIG. 16 is a side elevation view of another icebreaker;

FIG. 17 is a cross-sectional elevation view taken along line 17-17 in FIG. 16;

FIG. 18 is a cross-sectional elevation view taken along line 18-18 of FIG. 16;

FIG. 19 is a bottom plan view of a modified form of the force transferring sponsons illustrated in FIG. 16;

FIG. 20 is a view taken along lines 20—20, in FIG. 19;

FIG. 21 is a simplified elevation view of another vessel equipped with an integrated hull heating and hull pitching system; and

FIG. 22 is a simplified elevation view of another vessel equipped with an integrated hull heating and pitching system.

DESCRIPTION OF THE ILLUSTRATED EMBODIMENTS

An improved icebreaking vessel 10 according to this invention includes a positively buoyant hull 11 of generally conventional configuration and arrangement except in the bow portion 12 thereof which is described in greater detail below. Hull 11 includes a stern portion 13 and defines a centerwell 14 through the hull from main deck 15 to a keel 16 at about midships. Centerwell 14 preferably is centered on the centerline of the hull below a drilling rig 17 mounted to the vessel. The drilling rig includes a foundation structure 18 which defines a drilling platform 19 over which a conventional derrick structure 20 is mounted. A conventional rotary table 21 is mounted in the drilling platform over the centerwell.

The presence of centerwall 14 and drilling rig 17 in vessel 10 enables the icebreaking vessel to be used to advantage in arctic waters and the like as a floating drilling vessel in the manner which is known from the technology pertinent to offshore drilling. It will be appreciated that centerwell 14 and drilling rig structure 17 are not required on an icebreaking vessel according to this invention, but are illustrated in FIG. 1 merely to show that the improved icebreaking structures and procedures described herein may be incorporated into a vessel designed to serve some function other than only icebreaking. Thus, the improved icebreaking structures and procedures to which this invention is addressed may be incorporated into an oil tanker or some other ship, as well as into an icebreaker per se, without departing from the scope of the invention. Where the icebreaking vessel is constructed to serve the dual function of a floating drilling vessel, drilling rig 17 preferably also includes a conventional drawworks and associated equipment (not shown); in such a case, it is preferred that hull 11 include athwartships reversible thruster mechanisms 23 and 24 in the bow and stern portions of the hull, respectively, for generating thrust to port or to starboard, as desired, to improve the maneuverability of the vessel over an intended drill site, as well as to improve the maneuverability of the vessel when operated as an icebreaker.

Vessel 10 has a center of gravity 26 located approximately amidships above a center of buoyancy 27 when the hull has an untrimmed even-keel attitude. As explained in greater detail below, there are associated with the hull means which are at least partially pneumatically operated for shifting center of buoyancy 27 in a fore-and-aft direction at a selectable frequency. These pneumatically operated means are operative to accomplish this shift in center of buoyancy without significantly altering the displacement, i.e., total weight, of vessel 10 or the location of the center of gravity 26. The selectable frequency associated with operation of

the pneumatically operated means is correlated to the optimum composite icebreaking and ice-moving characteristic (energy transfer function) which exists between the hull and its proximate surroundings during icebreaking operation of the vessel. That is, the optimum composite energy transfer function takes into consideration the natural dynamic pitching characteristics of the hull per se, the properties and effects of an ice sheet 30 adjacent the hull which may modulate the natural dynamic pitching characteristic of the hull, and also the similar modulating properties and effects of broken ice present between the hull and the ice sheet in vessel 10.

The pneumatically operated means, in vessel 10, include a forward pitching chamber 28 and an aft pitching chamber 29, both of which are defined in the hull and open through the submerged surfaces of the hull, preferably through the keel of the hull, to water 31. The pitching chambers preferably are located as far as possible from the even-keel position of center of buoyancy 27, and are of the greatest volume possible consistent with the configuration of the hull as dictated by the many competing factors facing the naval architect in hull design. It is also preferred that the chambers have equal volumes and have their centroids of volume equally spaced from the even-keel center of buoyancy. In the event that the chambers are of different distances from the even-keel center of buoyancy or are of different volumes, it is desirable that the product of (1) moment arm from the even-keel center of buoyancy to the center of volume of one chamber and (2) the volume of that chamber be approximately equal to the same product for the other chamber.

A selectively operable mechanism is associated with the pneumatically operated means for applying air to the chambers for displacing water from each chamber and for admitting water to the chamber. Where both forward and aft pitching chambers are provided, as in vessel 10, these air applying and water admitting mechanisms are operated out of phase with each other. It will be recognized, however, that the vessel may include only a single pitching chamber, preferably located in the bow of the vessel for maximum pitching effect on an adjacent ice sheet 30; as a general rule, more volume is available forward of amidships for the pitching chamber than is available aft due to the fineness of the bow aft for efficient operation of the conventionally disposed and driven propeller 34 and other conventional propulsive machinery which usually are located aft.

In the case of vessel 10, as shown in FIG. 1, the selectively operable means for applying air and admitting water to the forward pitching chamber includes a source 35 of air at elevated pressures, such as a squirrel cage blower or compressor, an inlet duct 36 to source 35 preferably communicating from the main deck of the vessel, an outlet duct communicating source 35 and the upper portions of chamber 28, and an air exhaust duct 38 communicating between the upper portions of chamber 28 and the main deck, for example, and equipped with a valving device 39 for selectively opening or closing duct 38. Aft pitching chamber 29 of vessel 10 is equipped with a similar pressurized air source 40, an inlet duct 41 thereto, an outlet duct 37 therefrom, and an air exhaust duct 43 from chamber 29 equipped with a valving device 44.

The upper extents of fore-and-aft pitching chambers 28 and 29 (or of the single pitching chamber where only one is provided in the vessel) preferably are located below the even-keel load waterline 46 (see FIGS. 11 and 12) of vessel 10. As shown in FIG. 8 (which illustrates a pitching system 45 which is a modification of the arrangement shown in FIG. 1), the valving devices 39 and 44 for the pitching chambers, and also preferably the air pressurizing mechanisms for these chambers, are connected to a suitable control mechanism 47 which operates to cause air to be admitted to forward pitching chamber 28 while valving device 39 is closed, thereby to cause water to be displaced from chamber 28 by the pressurized air; this occurs at the same time that the valving device 44 associated with the aft pitching chamber is opened to cause water to be admitted to chamber 29 by reason of the hydrostatic head of water outside the chamber. Control mechanism 47 has a second state in which the relationships of valving devices 39 and 44 are reversed so that air is admitted to chamber 29 to displace water therefrom and to permit admission of water into forward pitching chamber 28.

In view of the foregoing description, it is apparent that pitching chambers 28 and 29, in conjunction with control means 47, function to effectively vary the configuration of hull 11 to produce fore-and-aft shifting of the location of center of buoyancy 27 relative to the stationary location of center of gravity 26. That is, when either of pitching chambers 28 or 29 is fully filled with air, the air-to-water interface adjacent the chamber is essentially continuous with the hull surfaces around the bottom of the chamber. When such a condition exists, the pressure of air in the chamber is equal to the hydrostatic head of water at the keel of the hull. This effect is the same as that produced by increasing the draft of the hull in the vicinity of the chamber, as by closing the hull over the bottom of the chamber, thereby producing a change in the distribution of buoyancy developed by the hull. This change in the buoyancy characteristic of the hull is accomplished without changing the net weight of the vessel. Thus, the center of gravity of the vessel remains stationary while the location of the center of buoyancy is shifted forward of the center of gravity when pitching chamber 28 is fully air filled, and by moving the center of buoyancy aft from the center of gravity when the aft pitching chamber 29 is fully air filled.

As soon as the center of buoyancy moves out of vertical alignment with the center of gravity, a couple is produced between the downwardly directed mass forces acting through the center of gravity and the upwardly directed buoyancy forces acting through the center of buoyancy, thereby imposing a pitching moment upon the hull. Thus, when pitching chamber 28 is fully air filled, the resulting pitching moment acts to cause the bow of vessel 10 to rise, and vice versa when aft pitching chamber 29 is fully air filled. Where the vessel has forward and aft pitching chambers, as shown in FIG. 1, the pitching chambers must be operated 180° out of phase with each other to generate maximum pitching moments. Where the pitching chambers are of equal volume and are equally spaced from the even-keel center of buoyancy, the synchronous in-phase operation of the pitching chambers will result in heaving of the vessel rather than pitching of the vessel.

It will be apparent that, where both forward and aft pitching chambers of given volume are provided, the magnitude of the pitching moment which can be produced will be twice the magnitude of the moment capable of being produced by a single chamber of the same given volume located the same distance from the even-keel center of buoyancy.

As noted above, prior icebreakers operated to break ice sheet 30 into pieces by converting the forward momentum of the vessel to either a downwardly directed force applied to the ice sheet or to an upwardly directed force applied to the ice sheet, such force being of sufficient magnitude to cause failure of the ice sheet. This was the basic principle of operation of prior icebreakers operated either in continuous or boxing modes. This invention, on the other hand, provides an icebreaking vessel in which pitching moments of substantial magnitude are developed by hull 11 by shifting the center of buoyancy of the hull relative to the center of gravity to produce vertical bow movements. These movements are of substantial magnitude and are generated at relatively low frequencies which correspond to the basic natural pitching frequency of the hull in pitching as modified by the effect of the ice sheet and broken ice closely adjacent to the vessel. Because the pitching moments developed by hull 11 by the structures and procedures of this invention are of substantial magnitude and produce substantial vertical excursions of the bow, the hull has substantial angular momentum during such pitching movements. This angular momentum is applied directly to the ice sheet in conjunction with the conventional forward momentum (and in conjunction with the vertical forces resulting from forward momentum by reason of the icebreaker bow configuration), thereby causing considerably more energy to be applied effectively by vessel 10 to ice sheet 30 than has previously been applied by a conventional icebreaker of the same displacement and propulsive power.

It was noted above that any floating body, depending on its dimensions and configuration, has a natural period in pitching (as well as in rolling, heaving, surging and the like) when floating at any given waterline. Focusing for the moment upon pitching, when pitching forces are applied to a floating hull of reasonably conventional configuration at intervals which correspond to the natural frequency of the hull in pitching, a resonance condition is produced in which pitching movements are considerably greater than pitching movements resulting from the application of pitching forces of the same magnitude but at other frequencies. One of the objectives of the present invention is to develop the maximum transfer of available energy from the hull to the ice sheet for the purposes of breaking ice sheet 30. Therefore, pitching chambers 28 and 29 of vessel 10 are alternately emptied of water and filled with water at intervals which correspond closely to the natural pitch frequency of hull 11. In this context, however, it must be understood that the natural pitch frequency of the hull is defined somewhat differently from what is conventional.

The terms "natural pitch period" or "natural pitch frequency" usually are used with reference to a hull floating in open water of substantially indefinite extent in all directions horizontally and vertically from the hull; for the sake of clarity in the following description, these properties are often referred to herein as "open-water natural pitch period" and "open-water natural

pitch frequency." The terms "icebreaking natural pitch period" and "icebreaking natural pitch frequency" are used herein to distinguish from the corresponding open-water properties of the hull. The "icebreaking natural pitch period" is defined as the open-water natural pitch period of the hull as modified by the presence of an ice sheet closely adjacent to the hull, and by the presence of broken ice between the hull and the ice sheet in the track broken through the ice sheet by the icebreaker vessel. The presence of a floating ice sheet closely adjacent to the vessel constitutes a boundary constraint on the water which alters the open-water natural pitch period of the hull. The presence of ice in the track between the ice sheet and the hull has the effect of altering the nature of the medium in which the vessel is floating, and this effect also results in a modification of the open-water natural period of the vessel. The "icebreaking natural pitch frequency" is defined as the open-water natural pitch frequency modulated by the effects of the floating ice sheet and of ice floating in the track between the hull and the ice sheet. Therefore, it is apparent that, during icebreaking operations, hull 11 and the hulls of the other icebreaking vessels described herein are considered as a component of an overall system which includes the hull, the adjacent ice sheet and broken ice between the hull and the ice sheet.

If cyclic pitching moments are applied to hull 11 at a frequency which even generally approximates the natural pitch frequency of the hull-ice system, the hull will begin to pitch and will tend to pitch at a frequency which corresponds to the natural pitch frequency. That is, if pitching moments are cyclically applied to the hull at a frequency which is within, say, 15 percent $\pm$ of the icebreaking natural pitch frequency of the hull, the hull will tend to seek its actual icebreaking natural pitch frequency. Accordingly, this invention contemplates that the mechanisms for applying pressurized air to the pitching chamber(s) of an icebreaker according to this invention, and for admitting water to the chamber(s), may initially be operated manually at some frequency which approximates the icebreaking natural pitch frequency of the hull when first beginning pitching mode operation of the icebreaker vessel from a steady-state even-keel condition. Once cyclic pitching movements of the hull have commenced, control mechanism 47 functions automatically to operate the air-applying and water-admitting mechanisms for the pitching chamber(s) in response to the uppermost and lowermost limits of travel of the bow of the vessel. For example, since the bow of the vessel will be moving vertically with no velocity at its upper and lower limits of travel, control mechanism 47 may include velocity monitoring devices which function, when they sense no vertical movement of the bow during pitching mode operation of the vessel, to shift the mechanisms associated with the pitching chamber(s) from an air-applying to a water-admitting condition, and vice versa.

Because the pitch-inducing mechanism illustrated in FIGS. 1 and 8 operates in resonance to the icebreaking natural pitch period of the vessel, it is apparent that large vertical excursions of bow 12 result when the vessel is operated in a pitching mode during icebreaking operations. These excursions may reach magnitudes of several feet rather than several centimeters; 1 inch equals 2.54 centimeters. The angular momentum of the bow as it passes through an even-keel state will be sub-

stantial, and this angular momentum is transferred to ice sheet 30, in conjunction with the forward momentum of the vessel, to break ice sheets of substantially greater thickness than have heretofore been broken by conventional icebreakers of equivalent displacement and power.

The angular momentum possessed by a pitching icebreaker according to this invention results in greatly enhanced icebreaking effectiveness of the vessel for a number of reasons which are complexly interrelated. It has been estimated that in conventional icebreakers only 5 percent of the available energy from the icebreaker is consumed in actually breaking the ice sheet, and that 80 percent of the available energy is consumed in moving broken ice between the hull and the ice sheet out of the way of the icebreaker; see FIG. 13, Lewis and Edwards' SNAME paper, supra. The unbroken ice sheet around the icebreaking vessel functions as a boundary constraint on water 31 to modulate the open-water natural pitch frequency of the hull. Because vessel 10 is pitching at relatively low frequency through large angular displacements during icebreaking operations, the hull itself acts as a pump on water in the track between the hull and the ice sheet. This pumping effect of pitching movement of the hull produces significant agitation and movement of the broken ice in the track, and this agitation assures that dynamic rather than static coefficients of friction exist between ice pieces engaged with the hull within the track. Since the dynamic coefficient of friction is less than the static coefficient of friction, it is apparent that hull 11 experiences less resistance to forward movement through the broken ice than in cases where the hull experiences no pitching or only very slight pitching movements during such forward movement. The result, therefore, is that, purely by reason of a reduction of the friction forces acting on the hull by broken ice in the track, a greater portion of the energy developed by vessel 10 is available for application by the hull to ice sheet 30 than is available from a conventional icebreaker of equivalent size and power.

Also, the pitch-related pumping action of the hull upon water in the track tends to keep ice pieces in the track completely away from the hull and to drive these ice pieces either onto or under the ice sheet along the margins of the track. The result is that icebreaking vessel 10, when operated in its induced-pitching icebreaking mode, is not required to overcome the buoyancy of ice pieces in the track to anywhere near the same extent as is required by icebreakers operated according to more conventional techniques. Of the 80 percent of the energy consumed by conventional icebreakers in moving broken ice out of the way of the hull in the ice track, a major portion of this energy drain is due to overcoming the buoyancy forces associated with broken ice pieces. That is, conventional icebreakers function to move ice out of the way of the vessel by engagement of these ice pieces with the hull and by movement of these ice pieces downwardly of the hull and then aft along the hull to the stern; this operation requires that the hull overcome the buoyant forces which are associated with the ice. With vessel 10, however, floating ice pieces are kept away from the hull by reason of the pitch-related pumping action of the hull on the water in the ice track and by reason of the impact of the hull on the ice pieces. A basic result, therefore, of the high amplitude, low frequency pitching movements of vessel

10 is to produce a substantial reduction in the 80 percent energy consumption factor pertinent to icebreakers of conventional design and operation.

The only other energy drain factor acting upon the hull (apart from the 5 percent factor already mentioned) is the energy required to overcome the wave making and skin friction resistance of the hull as it moves through the water; this energy drain factor is relatively constant at low speed-length ratios of the hull. Thus, any reduction in the 80 percent factor pertinent to conventional icebreakers produces a corresponding increase in the energy available for icebreaking and for moving through the broken ice. It is apparent, therefore, that the high amplitude, low frequency pitching movements of an icebreaker according to this invention are effective to make it possible for the vessel to apply a substantially greater portion of its available energy to the ice sheet for the purposes of actually breaking thicker ice at greater speeds than has heretofore been possible.

Referring again to FIGS. 1 and 8, FIG. 1 illustrates in a very simplified form the pneumatically operated means provided in an icebreaking vessel according to this invention for applying pressurized air to a pitching chamber and for admitting water to the chamber to produce the fore-and-aft shift in center of buoyancy in the manner described in detail above. As shown in FIG. 8, the pressurized air source 35 may be provided in the form of a pair of centrifugal blowers 48 and 49 which are serially connected so that the output of the first stage blower 48 is supplied to the input of second stage blower 49. The second stage blower has an outlet duct 50 which is selectably coupled via a valve 51 alternately to ducts 37 and 42, which communicate with the forward 28 and aft 29 pitching chambers, respectively. Valve 51 is operated by control mechanism 47. As shown in FIG. 8, the valve mechanisms 39 and 44 for regulating the discharge of air from pitching chambers 28 and 29, respectively, may take the form of damper valves also operated by control mechanism 47. Control mechanism 47 is arranged to cause second stage blower output duct 50 to communicate with duct 42 at the same time that air exhaust valve 39 for the forward pitching chamber is opened, and to cause second stage blower output duct 50 to communicate with duct 37 at the same time that valve 44 for the exhaust duct of the aft pitching chamber is open. Multi-staging of a plurality of centrifugal blowers makes it possible to pressurize large quantities of air to the pressure levels, say about 50 psig, required to displace water from the pitching chambers within the times appropriate.

Another pitching system 53 is shown in FIG. 3 and may be used to advantage in an icebreaking vessel according to this invention in conjunction with a pair of fore-and-aft pitching chambers or in conjunction with only a single pitching chamber within the vessel. In system 53, a source 54 of pressurized air may take the form of a squirrel cage or other centrifugal blower or any other suitable air pressurizing mechanism. The pressurized air source has an output duct 55 which communicates to the connection between a branch duct 56 and a by-pass duct 57. The communication of duct 55 to each of ducts 56 and 57 is regulated by a suitable valve 58 which is operated by control mechanism 47. Branch duct 56 communicates to the junction of a unified air supply and exhaust duct 59 and an exhaust duct 60. The communication of unified duct 59

to either branch duct 56 or exhaust duct 60 is regulated by a suitable valve 61 which is also operated by control mechanism 47. Unified duct 59 communicates from adjacent valve 61 to the upper extent of a pitching chamber 62 which is defined by hull 11 in its lower portions in such manner that the chamber opens downwardly through the hull to communicate with the water in which the hull floats. Exhaust duct 60 has an unvalved connection to by-pass duct 57, from which connection a discharge duct 63 communicates to the exterior of hull 11 preferably through the main deck of the hull. The junction between by-pass ducts 57 and exhaust duct 60 is arranged so that air flowing through the by-pass duct 57 exerts a pumping action, by means of a venturi effect, upon air in exhaust duct 60 adjacent the junction.

FIG. 3 illustrates that the actual mechanism relied upon to provide air source 54 is of the continuously operated form, i.e., a squirrel cage blower or other air compressor which operates continuously through several air-applying and water admission cycles in chamber 62.

Control mechanism 47 is arranged to have two basic operative states. In one state of the control mechanism, valves 58 and 61 are operated to provide communication between air source 54 and chamber 62 via ducts 55, 56 and 59. In its other state, the control mechanism operates valves 58 and 61 so that air may be exhausted from pitching chamber 62 via ducts 59, 60 and 63, and so that pressurized air from source 54 is supplied to discharge duct 63 via by-pass duct 57. It is apparent, therefore, that when the control mechanism is in its first state, air is admitted to chamber 62 under pressure from source 54, thereby to displace water from pitching chamber 62 and produce the shift in one direction of the center of buoyancy of hull 11. In its other state, the pressurized air in chamber 62 is vented from the chamber to the atmosphere via the discharge duct, thereby to allow water to be admitted to the chamber and to produce a shift in the opposite direction of the hull center of buoyancy. When control mechanism 47 is in its second state, the output from the continuously operating air pressure source is relied upon, via the venturi effect occurring at the junction between ducts 57, 60 and 63, to assist in pumping air from chamber 62, thereby to accelerate the flooding of the pitching chamber.

As shown in FIG. 3, a pair of closure doors 65 and 66 are movably mounted to hull 11 for retraction between a closed position shown in broken lines in FIG. 3, and an open position shown in solid lines in FIG. 3. In their closed position, the doors effectively seal the lower portions of pitching chamber 62 to the exterior of the vessel and are substantially continuous with the hull surfaces 67 peripherally of the lower extent of the pitching chamber. While the closure doors may be provided in any mounting arrangement desired, FIG. 3 shows that the closure doors may be mounted for reciprocation into and out of their closed position in response to the operation of a corresponding pair of double-acting ram assemblies 68, each of which has a piston rod 69 connected to the adjacent door through a suitable seal 70 disposed around the rod between the ram assembly and a recess 71 formed in the hull and in which the adjacent door is disposed when open so as not to restrict the opening of chamber 62 to the exterior of the hull. The doors, when closed, serve to re-

duce the resistance of hull 11 when operated in open water.

It will be understood that selectively operable closure mechanisms, such as doors 65 and 66, may be provided if desired in conjunction with the pitching chambers shown in FIGS. 1, 2, 4 and 5, for example; accordingly, the structure of such closure mechanisms is not illustrated in FIGS. 1, 2, 4 and 5.

Another pneumatically operated pitching system 72 for hull 11 is illustrated in FIG. 4 and includes a continuously operable air pressurizing device 54 which serves as a source of pressurized air within the system. Source 54 has an output duct 55 which is connected to the junction between an air supply duct 73 and a by-pass duct 74. The supply duct communicates to the upper extent of a pitching chamber 75 which may be the only pitching chamber in hull 11 or may be one of a pair of fore and aft pitching chambers. The by-pass duct communicates to the atmosphere through an upper portion of hull 11 as, for example, through the main deck 15 as shown in FIG. 4. A valve 76 is provided at the junction between ducts 55, 73 and 74 for controlling the communication of output duct 55 to either duct 73 or duct 74 in response to the operation of a control mechanism 47. When valve 76 is disposed to provide communication between ducts 55 and 73, duct 74 is isolated from air source 54 and, conversely, when the valve is disposed to provide communication between ducts 55 and 74, duct 73 is closed at a location spaced from pitching chamber 75.

Pitching system 72 also includes an air exhaust duct 77 which communicates between the upper extent of pitching chamber 75 and the exterior of hull 11. Such communication is controlled by a valve mechanism 78 which may be provided in the form of a multi-plate shutter valve, for example. Valve 78 is operated by control mechanism 47 in such manner that the valve is open when valve 76 is disposed to provide a communication between air source output duct 55 and by-pass duct 74. It is preferred that air exhaust duct 77 be of relatively large cross-sectional area so as not to unnecessarily restrict the flow of air through it and thereby impede the speed at which pitching chamber 75 is flooded during those periods of the operation of control mechanism 47 in which the pitching chamber is isolated from the pressurized air source.

As in the case of pitching systems 45 and 53, control mechanism 47 for system 72 is arranged to shift valve 76 between its two operative states, and to open and close valve 78, at intervals which correspond to the ice-breaking natural pitch period of hull 11, thereby to induce low frequency, high amplitude pitching movements of the hull in correspondence to the optimum energy transfer function existing between hull 11 and its immediate surroundings during icebreaking operation of the vessel.

Still another pitching system 80 is shown in FIG. 5 and may be used to advantage in vessel 10 or in any of the other vessels according to this invention. In system 80, source 54 of pressurized air is provided in the form of the air compressor portion 81 of a gas turbine 82. Turbine 82 may be provided aboard vessel 10 for supplying electrical power within the vessel, and to this end the rotor 83 of the gas turbine is connected via a power take-off mechanism 84 to an electric power generator 85. Air at high pressure, say 50 pounds per square inch gauge, is obtained from a selected location

within the compressor, say in the second stage of the compressor, and is supplied via a supply duct 86 to a pitching chamber 87. The pitching chamber, like the pitching chambers previously described, is provided in the lower portion of hull 11 and opens through the bottom surface of the hull at a desired location in the hull spaced as far as possible, preferably forwardly, from the even-keel position of the center of buoyancy. As noted above, pitching chamber 87 may be provided with retractable closure doors (see FIG. 3), if desired.

A valve 88 is provided in supply duct 86 between the compressor and the pitching chamber to isolate the pitching chamber from turbine 82 during those phases of the operation of system 80 in which water is admitted to pitching chamber 87. Valve 88 is disposed in duct 86 in association with a by-pass duct 89. The valve is switched between its two operative positions in response to the operation of control mechanism 47. In one operative position, the valve closes by-pass duct 89 and provides communication between the compressor and the pitching chamber. In its other operative position, the valve provides a communication between ducts 86 and 89 and isolates the pitching chamber from turbine 82.

By-pass duct 89 extends to an eductor nozzle 90 disposed in a venturi throat portion 91 of an air exhaust duct 92 from the upper extent of pitching chamber 87. A valve 93 is disposed in the exhaust duct and is operative to close or open the exhaust duct in response to the operation of control mechanism 47. Valve 93 is open when valve 88 is positioned to open duct 89 to duct 86 so that the discharge of compressed air from nozzle 90 causes the venturi to function as an eductor pump to extract air from pitching chamber 87 and thereby augment the flooding of water into the pitching chamber. From the foregoing description, it will be apparent that control mechanism 47 for system 80 is operated cyclically at intervals which correspond to the icebreaking natural pitch period of vessel 10, for example.

Another pneumatically operated pitching system 95 is shown in FIG. 6 and includes a continuously operating source 54 of pressurized air having an output duct 55 which communicates to an accumulator 96. The accumulator is connected via an outlet duct 97 and a valve 98 to a unified air supply and exhaust duct 99 which opens to a pitching chamber 100 defined in the lower portion of hull 11 to open to keel surfaces 16 of the hull. Valve 98 is operated by control mechanism 47 to provide communication between ducts 97 and 98 in one state of the valve, and to provide communication between duct 99 and an air exhaust duct 101 which functions to vent pressurized air from pitching chamber 100 to the atmosphere via the upper portions of the vessel. When airflow communication exists between ducts 97 and 99, air is admitted under pressure to pitching chamber 100 to displace water from the chamber. On the other hand, when valve 98 is disposed to provide communication between ducts 99 and 101, the pressure of air in the pitching chamber is reduced, thereby permitting water to be admitted into the pitching chamber from below the hull.

As shown in FIG. 6, it is preferred that pitching chamber 100 be defined as a recess formed in the lower extremity of the hull as far forward or aft as possible from the even-keel center of buoyancy of the vessel. It is preferred that the recess be dish-shaped, concave

downwardly from the hull. A flexible air-impervious membrane 102 is disposed across the lower portions of the pitching chamber and is sealed to the hull circumferentially of the recess as at 103. Preferably, membrane 102 is arranged so that, when the pitching chamber is fully charged with pressurized air, the membrane protrudes downwardly from the lower surfaces of the hull and so that, when valve 98 is disposed to provide communication between ducts 99 and 101, the membrane conforms to the surfaces of the recess defining the pitching chamber. It is apparent, therefore, that the effective volume of pitching chamber 100, when the chamber is fully charged with compressed air from accumulator 96 and source 54 is approximately double the volume of the recess actually formed in hull 11. This arrangement makes it possible to impose upon hull 11 substantially larger upward pitching forces than would be possible if membrane 102 were not provided. Stated in another way, an upward pitching force of given magnitude can be achieved through the use of a pitching chamber which is approximately half the volume of the corresponding pitching chambers of systems 45, 53, 72 and 80, for example.

Also, the inclusion of accumulator 96 in pitching system 95 makes it possible for the pitching system to incorporate an air pressure source, such as a compressor or blower, of smaller capacity and horsepower than would be the case in the arrangements described above for systems 45, 53, 72 and 80. This is true because, during those periods when water is being admitted to the pitching chamber by movement of membrane 102 from its fully extended condition to the condition shown in broken lines in FIG. 6, in which the membrane conforms to the configuration of the recess, the output from continuously operative air source 54 is being stored in accumulator 96 for use in charging the pitching chamber with compressed air when valve 98 is moved to its other operative condition. If desired, an accumulator may be incorporated in any of systems 45, 53, 72 and 80.

FIG. 6 clearly illustrates that pitching system 95, as well as pitching systems 45, 53, 72 and 80, functions to effectively vary the configuration of hull 11, and the distribution of buoyancy developed by the hull, in a cyclic manner in response to operation of control mechanism 47. This cyclic change in the buoyancy distribution characteristic of the hull is accomplished without varying the effective weight of the hull; in this regard, it may be said that pitching systems 45, 53, 72, 80 and 95 are massless pitching systems.

FIG. 7 is a simplified cross-sectional plan view at about the load waterline of the forward portion of another icebreaking vessel 110. Vessel 110 has a bow portion 111 which gives the vessel, in plan view, somewhat of an arrowhead configuration in that the hull 112 flares outwardly in the conventional manner from stem 113 to a portion of increased beam, as at station 114, well forward of amidships of vessel 110 and proximate stem 113. Proceeding aft along the hull from location 114, the hull decreases in beam to a station 115 of reduced beam. Aft of station 115 the hull increases in beam to about amidships where the hull may have a beam as great as or greater than the beam of the hull at station 114. Between stations 114 and 115, the surfaces of hull 112 open toward the stern of the vessel. The configuration of hull 110 illustrated in FIG. 7 is representative of the hull at about its load waterline,

below the load waterline, and for some distance above the load waterline, if desired.

Icebreaking vessel 110 is equipped with a pitching system 117 which includes a pitching chamber 118 defined as a tank 119 defined within hull 112 forward of station 115, preferably adjacent increased beam station 114. An air supply duct 120 (see FIG. 8) communicates to the upper extent of tank 119 from a suitable source of pressurized air via a valve 121. An air exhaust duct 122 is provided from the tank on each side of the vessel, as shown in FIG. 7, and each duct communicates from the upper aft portion of the tank to the exterior of the hull via a discharge opening 123. A valve 124 is provided for each air exhaust duct 122 and is operated by a suitable control mechanism 47 to either open or close the duct.

A water inlet duct 125 communicates through the lower portion of hull 112 to tank 119, preferably at the lower forward portion of the tank. The water inlet duct is equipped with a valve 126 which is arranged so that, when the valve is fully open, the structure of the valve presents the minimum possible resistance to water flow through the duct to tank 119. Valve 126 is connected to control mechanism 47 for operation between its open and closed states by the control mechanism. Port and starboard water discharge ducts 127 communicate from the opposite lower aft extents of tank 119 to the exterior of the hull. As shown in FIG. 8, each water discharge duct 127 preferably shares a corresponding discharge opening 123 with the adjacent air exhaust duct. Each water discharge duct is equipped with a valve 128 which preferably is similar to the water inlet control valve 126. Valves 128 are coupled to control mechanism 47 for operation by the control mechanism.

Valves 121, 124, 126 and 128 are connected to control mechanism 47 so that, when valves 121 and 128 are open, air is admitted under pressure to tank 119 to displace water from the tank through discharge openings 123; during this portion of a cycle of operation of pitching system 117, valves 124 and 126 are closed. Control mechanism 47 is operative during a different phase of the cycle of system 117 to open valves 124 and 126 and to close valves 121 and 128, so that the air pressure in tank 119 is relieved via ports 123 and so that water may flow into and flood tank 119 via duct 125.

It is preferred that the opening of water inlet duct 125 to the submerged surfaces of hull 112 be located along the centerline 129 of vessel 110. This arrangement assures that the water entering pitching chamber 118 when valve 126 is open will be as free as possible of pieces of ice broken from a surrounding ice sheet during pitching mode operation of icebreaking vessel 110.

It will also be understood that bow portion 111, in addition to being configured as specifically described and illustrated, is also arranged in other respects to serve the function of an icebreaker. That is, in addition to possessing the features shown in FIG. 7, bow portion 111 of vessel 110 may resemble a conventional icebreaker, or it may be arranged as shown in FIGS. 12 or 14, for example.

It is apparent, from the foregoing description of icebreaking vessel 110, that pitching system 117 is operative, either under manual control or control of mechanism 47, to induce pitching movements of substantial magnitude in vessel 110 when engaged in icebreaking

operations, and that these pitching movements are induced in the manner described above.

The arrowhead configuration of bow portion 111 provides several advantages in an icebreaking vessel. This bow configuration provides substantial beam to the vessel well forward of amidships, closely adjacent to the stem of the vessel. This makes it possible for the vessel to incorporate a pitching chamber of substantial volume much farther forward of amidships than would be the case if hull 112 were of conventional configuration. Also, the arrowhead configuration of bow portion 111 makes it possible for air and water to be discharged from pitching chamber 118 toward reduced beam station 115 to flow rearwardly along the surfaces of the hull with considerable velocity and momentum. This rearward discharge of the air and water from pitching chamber 118 causes pieces of ice present in the track between vessel 110 and the adjacent ice sheet to be carried rearwardly along the hull. Thus, as pitching system 117 is operated to induce pitching movements of hull 112, ice broken from the surrounding ice sheet is transported along the track to the rear vessel. In view of the discussion which has already been presented concerning the 80 percent energy drain factor pertinent to icebreakers of conventional configuration, it is apparent that the arrangement shown in FIGS. 7 and 8 contributes to a reduction in this energy drain factor. That is, the arrangement shown in FIGS. 7 and 8 applies much of the energy expended in inducing pitching movements in the vessel to assist in moving broken ice rearwardly out of the way of the vessel, thereby making it possible for the vessel to apply to the ice sheet a greater fraction of its overall available energy than has heretofore been possible.

Another icebreaking vessel 130 according to this invention is depicted in FIG. 9 which is a much simplified plan view through the bow portion of the vessel at about its load waterline. As shown in FIG. 9, vessel 130 includes a hull 131 the bow portion of which includes separate port and starboard pitching wing tanks 132 and 133 disposed on opposite sides of the vessel centerline 134. As shown in FIG. 10, the wing tanks extend vertically of hull 131 from the centerline adjacent the keel to adjacent the gunwale. Each tank has an inner wall 135 and an outer wall 136. The inner wall 135 of each tank is arranged to be essentially continuous with the exterior surfaces of hull 131 aft of the tanks. Accordingly, outer tank wall 136 is arranged, at the aft end of each tank, to intersect inner wall 135 so that the outer surfaces of the outer wall of each tank open generally toward the stern of vessel 130.

The basic outline of each tank 132 and 133 is completed by a top plate 137 which extends between the inner and outer walls of the tank at about the gunwale of vessel 130. A partition member 138 is disposed transversely of each tank a selected distance below top plate 137 to define an air distribution plenum chamber 139 in the upper portions of each tank. Air at suitable pressure levels is supplied to the plenum chamber of each tank via an inlet duct 140 from a suitable air source, such as a multi-stage compressor 141.

A plurality of ports 142 are formed through partition member 138 at selected locations along the partition member in each tank. These ports are provided for admitting air at high pressure from chamber 139 into the lower volume of each tank, which volume constitutes a pitching chamber. Also, as shown in FIG. 11, a plural-

ity of ports 143 are formed through the top plate of each tank for allowing air under pressure to be exhausted from the adjacent pitching chamber during the flooding of the chamber during pitching mode operation of vessel 130. FIG. 11 illustrates that ports 142 and 143 are staggered relative to each other along the length of tanks 132 and 133, and that ports 143 are located at the upper ends of corresponding exhaust ducts 144 which open to the respective tanks through partitions 138. The ducts do not close the plenum chambers so that continuity is maintained within the plenum chambers along the length of each of tanks 132 and 133.

A valve member 145, 146 is provided for selective closure of each of ports 142 and 143, respectively, to regulate the flow of air through the ports to admit air under pressure to the pitching chambers and to vent pressurized air from these chambers.

The valve members are carried by respective piston rods 147 and 148 of corresponding actuating ram assemblies 149 and 150. Each piston rod is connected to a piston 151 and 152 via suitable seals formed at the opposite ends of the ram assembly cylinders disposed within plenum chamber 139 and ducts 144, respectively. Pilot air ducts 153 and 154 are connected from a pilot valve assembly 155 to ram assemblies 149 and 150, respectively. Duct 153 is connected to its cylinder below piston 151 for valve member 145, whereas duct 154 is connected to its cylinder above piston 152 for air exhaust valve member 146. Pilot valve assembly 155 is operated by a suitable control mechanism 47 (see FIG. 10), and is arranged so that, depending upon the nature of the signal received by it from the control mechanism, one or the other or both of ducts 153 and 154 is connected via the pilot valve assembly to a pilot pressure supply duct 156. Duct 156 extends from the pilot valve assembly to a source of air at pilot pressure, which pressure preferably is greater than the pressure of air supplied via duct 140 to plenum chamber 139. As shown in FIG. 10, the pilot pressure air source may be a higher pressure stage of compressor 141 than the stage relied upon to provide air through duct 140 to plenum chamber 139.

As shown best in FIG. 11, valve member 145 for each of ports 142 is disposed below partition 138, whereas valve member 146 for each of ports 143 is disposed above tank top plate 139. Each of these valve members are biased by the air pressure in chamber 139 or the adjacent pitching tank into their open position. The valve members, however, are held in their closed positions by pilot air applied to the adjacent face of the corresponding piston in ram assemblies 149 and 150. Accordingly, it is apparent that the product of (1) pilot air pressure P_2 supplied to the ram assemblies and (2) the effective area of each of pistons 151 and 152 must be greater than the product of (3) the air pressure P_1 in chamber 139 (or ducts 144) and (4) the effective area of valve members 145 and 146, respectively, if the pilot air is to be effective to hold the valve members closed, as shown in FIG. 11. When it is desired to admit air under pressure from plenum 139 to the lower volumes of tanks 132 and 133, pilot valve assembly 155 is operated to effectively isolate duct 153 from pilot air supply duct 156; valve 145 then opens in response to the presence of P_1 presented to its upper surface. Similarly, valve 146 is opened by disposing pilot valve assembly 155 in such a condition that duct 154 is effectively isolated from the pilot air

supply duct, thereby enabling the pressure of air in duct 144 to drive the valve member to its open position.

The air supply ports 142 for tanks 132 and 133 are open when the air venting ports 143 for the tanks are open, and vice versa. Ports 142 are opened to admit pressurized air to the wing tanks for displacing water from the tanks. Conversely, ports 143 are opened to vent air from the tanks so that the tanks may be flooded with water as described below. When ports 142 are closed, the plenum chambers function as accumulators for air discharged to them from compressor 141.

The water admitting and discharging means for each of pitching wing tanks 132 and 133 includes one or more large area flooding openings 163 formed through the outer wall 136 of each tank adjacent the centerline 134 of the vessel. Each flooding opening is fitted with a closure member 164 which operates like a check valve so that water flows only from the exterior of the vessel into the pitching tank, and not in the reverse direction when air is admitted under pressure to the tank. As shown in FIG. 10, each closure member for a flooding opening preferably is pivoted as at 165 to the outer tank wall and is biased by a suitable mechanism 166 into a closure position across the adjacent flooding opening. Each flooding opening and its associated closure member is pressure sensitive to provide communication between the exterior of the vessel and the adjacent pitching tank only when the pressure in the tank is less than the pressure of water outside the vessel adjacent the flooding opening.

The water discharge means from each pitching wing tank includes a plurality of discharge nozzles 168 arranged in the outer walls 136 of the tank is a grid-like array extending both horizontally and vertically along the extent of the pitching tank. Each discharge nozzle is provided in conjunction with a device 169, such as a float or float-operated device, which is sensitive to the presence of air in the tank adjacent the corresponding discharge nozzle to seal the nozzle. Thus, each nozzle is operative to permit only water to flow through it to the exterior of the vessel and not air. As air under pressure is admitted to each pitching wing tank from the source of pressurized air, devices 169 sense the air-water interface in the tank and close those nozzles located above the interface. In this manner, air pressure is maintained in the tank and water is discharged from the tank only through those nozzles which are submerged within the tank.

Discharge nozzles 168 are arranged to impart substantial velocity and momentum to water being discharged by them, thereby to form a plurality of jets of discharged water, the several jets being represented by arrows 170 in FIGS. 9 and 10. The nozzles 168 are arranged so that jets 170 are directed essentially athwartships of the vessel, i.e., essentially perpendicular to centerplane 134. Proceeding downwardly along the vessel, the nozzles are directed more and more vertically as shown in FIG. 9. An inspection of FIGS. 9 and 10, therefore, shows that discharge nozzles 168 are effective to impart substantial momentum to water being discharged by them and to direct such energy to cause broken ice, floating in the ice track between vessel 130 and an adjacent ice sheet, away from the hull. Accordingly, the energy developed by the water discharged from the tank when air is admitted to the tank under pressure from compressor 143 is conserved and is turned to advantage to assist in moving ice out of the

way of the vessel as it proceeds through an adjacent ice sheet during icebreaking operations, thereby greatly reducing the buoyant ice forces acting on the vessel and contributing greatly to the 80 percent energy drain factor referred to above.

FIG. 10 illustrates that port and starboard bow pitching wing tanks 132 and 133 may be provided as add-on structure to an existing hull 131 which may originally have been constructed as an icebreaker or some other type of vessel. That is, this invention contemplates that the inner walls 135 of pitching tanks 132 and 133 may be defined by the outer hull surfaces of an existing vessel, and that outer tank walls 136 may be provided during the process of converting an existing vessel into a pitching icebreaking vessel according to this invention.

It will be apparent that, because wing tanks 132 and 133 are separated from each other by a centerline bulkhead 171 (see FIG. 9), they may be operated as rolling or heeling tanks if port valves 145 and starboard valves 146 are operated synchronously. Also, where counterparts of tanks 132 and 133 are provided in the stern of vessel 130, as is contemplated by this invention, they too may be operated as heeling tanks. The presence of separate port and starboard fore-and-aft tanks makes it possible for vessel 130 to be pitched, rolled, heaved, or wallowed, as desired, at any frequency desired, thereby reducing to the minimum the possibility that the vessel may become fast in the ice during icebreaking operations.

It should also be apparent that the pitching chambers previously described relative to FIGS. 1 through 8 may also be equipped with centerline bulkheads to enable them to be operated to induce rolling motion of the vessel.

From the foregoing description, it is apparent that this invention provides an icebreaking vessel which is effective, because of its induced pitching motion in substantial resonance to the icebreaking natural pitch period of the vessel, to operate in an ice sheet in a manner consistent with the optimum pitch energy transfer characteristic existing between the vessel and the ice sheet. The result is that an icebreaking vessel according to this invention is effective to usefully apply substantially more of the energy available from the vessel to actually breaking ice at increased speeds. Also, as shown in FIGS. 12 through 15, this invention provides improved bow configurations for icebreaking vessels. These improved bow configurations enable the present icebreaking vessel to transfer its greater available energy more efficiently to an ice sheet than has theretofore been possible. The improved bow configurations shown in FIGS. 12 through 15 are arranged so that they are effective to apply force directly to an ice sheet immediately ahead of the vessel and in the vicinity of the bow during both upward and downward pitching excursions of the bow. Therefore, icebreaking energy is transferred essentially continuously by the improved icebreaking vessel to the ice sheet, making it possible for the vessel to proceed rapidly through ice sheets of substantially greater thickness than have heretofore been broken by ships of a given size and displacement.

As shown in FIGS. 1, 12 and 13, icebreaking vessel 10 has its bow portion 12 configured so that the stem 173 of the bow is reversely raked at about the location of the load waterline 46 on hull 11. To facilitate further

description of the improved bow configurations shown in FIGS. 12 through 15, the term "positive rake" is defined as rake which proceeds from fore to aft of the vessel proceeding downwardly from the main deck toward the keel of the vessel. "Negative rake," on the other hand, is rake which proceeds from the stern toward the bow of the vessel proceeding downwardly from adjacent the main deck toward the keel. Thus, stem 173 of vessel 10 has moderate positive rake in its upper extent at and adjacent to the forepeak of the vessel, i.e., adjacent the intersection of stem 173 and main deck 15. A selected distance above load waterline 46, however, stem 173 is turned sharply toward the stern of the vessel in a portion 174 of high positive rake. At about the load waterline 46, stem 173 is reversely curved to merge into a portion 175 of high negative rake which lies essentially below load waterline 46. The lower forward end of negatively raked portion 175 is faired into the keel to define a structure which resembles a bulbous bow or submerged ram arrangement in hull 11. Portions 174 and 175 of high positive and negative rake, respectively, intersect each other in the reversely curved portion of stem 173 to define a throat area 176 in the icebreaker bow configuration of vessel 10. Preferably the spacing between the forward ends of highly raked portions 174 and 175 of bow 12 is greater than the maximum thickness of an ice sheet 30 capable of being broken by icebreaking vessel 10 when operated in its induced pitching mode.

During icebreaking operation of the vessel, the margin of ice sheet 30 immediately adjacent to the vessel is engaged between highly raked portions 174 and 175 adjacent but preferably not fully within throat 176. As shown in FIG. 12, during downward excursions of bow 12 in response to induced pitching movements of the vessel, the downwardly opening stem portion 174 engages the upper surface of ice sheet 30 to effectively apply the angular and forward momentum of the vessel to the ice sheet. On the other hand, during upward pitching movements of the vessel, as when forward pitching chamber 28 has the water discharged therefrom, the underside of ice sheet 30 is engaged by stem portion 175 (see FIG. 13), thereby to apply the energy derived from forward and angular momentum of the vessel to the ice sheet. From an examination of FIGS. 12 and 13, it is apparent that when icebreaking vessel 10 is operated in its induced pitching icebreaking mode, the vessel in effect saws its way through ice sheet 30 and thereby progresses through the ice sheet in any desired direction much more rapidly and efficiently than has heretofore been possible.

FIGS. 14 and 15 illustrate the bow 178 of another icebreaking vessel 179 according to this invention. In bow 178, stem 173 has a portion 180 of moderate positive rake adjacent the forepeak of the vessel. Stem portion 180 is faired at its lower end into a portion 181 of high positive rake which extends to a reversely curved section 182 below which the stem manifests high negative rake, as at 183. At its lower forward end, negatively raked portion 183 is faired into a second lower stem portion 184 of high positive rake. Stem portions 183 and 184, if extended, would intersect each other approximately on an extension of the load waterline 46 of the vessel, and between them, define an icebreaking nose structure 185 in bow 178; it will be appreciated, however, that negatively raked portion 183 may proceed directly from a downwardly extended normally

raked stem portion 180 so that nose 185 is defined forward of the forepeak of vessel 179. Intermediate nose structure 185 and the keel of vessel 179, stem portion 184 of high positive rake is faired into a portion 186 of the stem in which the stem manifests a moderate rake as is conventional in icebreakers such as those of the U.S. Coast Guard Wind-class icebreakers. In other words, but for the presence of nose structure 185 between stem portions 181 and 186, the configuration of bow portion 178, when viewed in elevation as illustrated in FIGS. 14 and 15, resembles the configuration of conventional icebreakers such as those of the Wind-class.

As shown best in FIGS. 14 and 15, nose structure 185 functions to effectively transfer the angular and forward momentum of vessel 179 to ice sheet 30 during both upward and downward pitching excursions of the bow when the vessel is operated in its induced pitching icebreaking mode. During upward excursions of the bow, nose structure 185 rides up over the top of ice sheet 30 so that stem portion 184 of high positive rake may engage the upper surface of the ice sheet during the subsequent downward excursion of the bow. During such downward excursions, nose structure 185 deflects the ice sheet downwardly and ultimately breaks through the ice sheet. After nose structure 185 has broken through the ice sheet during a downward excursion of the bow, the forward momentum of vessel 179 carries nose structure 185 under ice sheet 30 so that stem portion 183 of high negative rake may engage the underside of the ice sheet during the subsequent upward excursion of the bow. At about the upward limit of the upward excursion of the bow, nose structure 185 again breaks through the ice sheet so that the forward momentum of vessel 179 carries the nose structure into position over the upper surface of the ice sheet, as shown in FIG. 14.

When an icebreaking vessel according to this invention is provided with a bow configuration similar to that shown in FIG. 1, throat portion 176 functions to assure that the vessel cannot be run sufficiently far up onto the top of ice sheet 30 to result in beaching of the vessel on the ice sheet. When the vessel is equipped with a bow configuration like or similar to bow configuration 178, then stem portions 182 and 186 function to assure that the vessel will not be beached on ice sheets of thickness greater than can efficiently be broken by the vessel even during periods of induced pitching mode operation.

FIG. 16 shows, in elevation, another icebreaking vessel 190 according to this invention. While the same is not illustrated, it will be understood that vessel 190 is equipped with a pitch-inducing mechanism of the type described above or shown in FIGS. 1 through 11, for example. Also, FIG. 16 illustrates that vessel 190 has a bow structure 191 which, for the sake of example, is shown to be of generally conventional configuration in basic form. That is, the stem 192 of bow structure 191 has an upper portion 193 of moderate positive rake which is faired into a portion 194 of high positive rake beginning somewhat above the load waterline of the vessel and proceeding partially to the keel 195 of the vessel. Stem portion 193 is faired into a lower stem portion 196 of moderate positive rake below the load waterline.

An ice forcing sponson 198 is rigidly secured to the sides of vessel 190 generally along the waterline of the

vessel which is associated with downward pitching of the vessel in response to operation of the pitch-inducing mechanisms provided in the vessel. While it is not shown in FIG. 16, a sponson 198 is provided along each of the port and starboard sides of the vessel. Each sponson has a forward end 199 located rearwardly of, but adjacent to stem 192 and an aft end 200 located at about amidships of vessel 190 where the vessel normally has its maximum beam. FIGS. 17 and 18 are cross-sectional elevation views taken at aft and forward stations of the starboard sponson. FIGS. 17 and 18, in conjunction with FIG. 16, show that the sponsons are of generally triangular configuration and have upper and lower surfaces 201 and 202, respectively, which intersect each other outboard of hull 203 for vessel 190. Hull 203 provides the third leg of the triangular cross-sectional configuration of each sponson.

As shown best in the combination of FIGS. 16, 17 and 18, the upper and lower surfaces 201 and 202 of each sponson 198 are warped so that, at the aft end of the sponson, lower surface 202 is substantially more parallel to the vertical centerplane of vessel 190 than is the same surface at the forward end of the sponson. Thus, FIG. 17 shows surface 202 with substantial slope, whereas FIG. 18 shows the surface with little slope. It is apparent, therefore, that as icebreaking vessel 190 is pitched during icebreaking operation of the vessel, each sponson, during a downward excursion of bow 191, moves progressively into engagement with an ice sheet adjacent the vessel. That is, during a downward pitching excursion of the bow of vessel 190, sponsons 198 first engage the ice sheet adjacent the rear ends of the sponsons, and the area of engagement between the sponsons and the ice sheet increases proceeding toward the bow of the vessel. Initially, the force applied by the sponson adjacent its rear end is directed primarily outwardly of the vessel, but the principal vector of each increment of applied force rotates into a substantially vertical plane progressing toward the front end of the sponson during further downward movement of the bow. Thus, each sponson functions adjacent its aft end to force the ice sheet and broken ice adjacent the vessel outwardly from the vessel, but forces such ice near the bow of the vessel primarily downwardly. This action of the sponsons on ice and ice pieces adjacent the vessel tends to keep the ice track free of ice which would otherwise forcefully engage the hull and consume energy available from the icebreaker. This action also smoothly transfers angular momentum of the vessel during downward pitching moments to the ice sheet. Thus, sponsons 198 provide for controlled application of vertical forces to the ice sheet rather than hammering of the ice sheet. Also, to the extent that the sponsons become submerged during downward pitching of the vessel, the sponsons act as a pump on water adjacent the vessel and on ice floating in such water. This pumping action of the vessel, as noted above, tends to keep floating ice adjacent the vessel well clear of the hull of the vessel, thereby still further reducing the 80 percent energy drain factor reviewed above.

The lower surfaces 202 of sponsons 198 are continuously curved along the entire length of the sponsons. FIGS. 19 and 20, on the other hand, illustrate additional sponsons 210 according to this invention. Each of sponsons 210 has an upper surface 211 and a lower surface 212. In contrast to lower surfaces 202 of sponsons 198, lower sponson surfaces 212 are discontinuously

curved in the manner illustrated in FIG. 20. Thus, in FIG. 20 the broken line 213 represents the point of intersection of sponson lower surfaces 212 with the hull if the sponson lower surfaces were continuously curved in the manner of the lower surfaces of sponsons 198. As apparent from FIG. 20, however, sponson lower surfaces 212 are arranged to define structure resembling ratchet teeth. In other words, sponson lower surface 212 is constituted of a plurality of individual ice-engaging surface segments 214, each of which intersect the hull at their rear ends above imaginary line 213 and which intersect hull 203 at their forward ends at line 213. Each inclined surface segment 214 also has associated with it at its forward end a vertical surface 215. Considered as overall entities, surfaces 211 and 212 are warped in the same manner as sponson surfaces 201 and 202 described above.

Sponsons 210 function in the same general manner as sponsons 198 during pitching operation of vessel 190. Sponsons 210, however, are effective to apply downward force to the adjacent ice sheet or to ice as a series of impulses, rather than in a substantially smoothly variable manner, as described above.

It will be understood that where sponsons of the type shown in FIGS. 19 and 20 are provided on a pitching icebreaking vessel, it is desirable that segments 214 of sponson lower surface 212 be inclined in the manner shown in FIG. 20 relative to the bow of the vessel. The inclination of these surface segments in a manner reversed to that shown in FIG. 20 would result in the sponson lower surface defining a plurality of teeth which would bite into the ice sheet and restrict the vessel from being backed off of the ice sheet in the event the vessel tends to beach on the ice sheet during ice-breaking operations.

In FIG. 16, broken line 217 represents the limits of a heated area 218 provided in the side surfaces of hull 190 over at least the forward half of the length of the vessel in those portions of the hull surface which experience variable immersion in response to induced pitching of the vessel during icebreaking operations. As shown best in FIGS. 17 and 18, heated area 217 includes the lower surface 202 of sponsons 198, or the corresponding surfaces of sponsons 210, where sponsons are provided in the vessel. The heating mechanism coupled to area 218 may include a plurality of electrical resistance elements 219 intimately engaged with the inner surfaces of hull 203 and the lower surfaces of the sponsons. It will be understood, however, that any suitable heating mechanism may be associated with the hull and hull appurtenances over areas 216, and such mechanisms may be water bath heating arrangements or heated fluid circulating coils intimately engaged with the hull surfaces. Regardless of the heating mechanism actually provided, it is relied upon to heat the adjacent exterior surfaces of hull 203 sufficiently that such surfaces are maintained at a temperature above the freezing point of water in the environment of the icebreaking vessel. That is, where the icebreaking vessel is used to break ice formed in fresh water, a different temperature may have to be maintained by heating mechanisms 219 than would be the case where the same vessel is operated to break ice formed over salt water.

Heated areas 216 in icebreaking vessel 190 are particularly effective where the vessel is used to break snow-covered ice. It has been observed, particularly in conjunction with icebreaking operations in the Beau-

fort Sea as well as in icebreaking operations on the Great Lakes, that ice sheets covered with a layer of snow have a much greater tendency to adhere to the wetted surfaces of the icebreaker than where the ice sheet has no snow cover, especially when the ambient temperature is considerably below freezing. To the extent that broken ice adheres to or intimately engages the surfaces of the vessel, such ice greatly increases the virtual mass of the vessel, thereby significantly increasing the skin friction and wave making resistance of the vessel. The presence of ice adhered to the surfaces of the icebreaker also substantially compounds the problem of moving broken ice out of the way of the vessel within the ice track. The provision of heated areas 216, on the other hand, prevents broken ice, particularly ice broken from a snow-covered ice sheet, from adhering to the hull, thereby making it possible for the hull to transfer its available energy to the ice sheet for icebreaking purposes. Preferably, heated areas 216 extend along the load waterline at selected distances above and below the load waterline proceeding rearwardly of the vessel from adjacent stem 193 to a point aft of the maximum beam of the vessel.

Also, it has been found that the coefficient of friction of snow against steel, particularly wind-driven snow in the Arctic, may be as much as four times greater than the coefficient of friction, either static or dynamic, of ice against steel. Heated areas 216 in icebreaking vessel 190 assure that, to the extent that snow-covered pieces of broken ice engage the hull of the vessel, the snow is melted to provide a lubricant against the side of the hull, thereby greatly reducing the coefficient of friction which the vessel must overcome to progress through the ice.

FIG. 21 depicts another icebreaking vessel 240 which integrates the hull heating feature previously described with reference to vessel 190 and the induced pitching features described with reference to FIGS. 1 through 15, for example. The hull 241 of vessel 240 defines a forward pitching chamber 28 and an aft pitching chamber 29. Extending along the major portion of the length of the hull, preferably from closely adjacent icebreaking bow 242 to substantially aft of amidships, is an air circulating chamber 243 the outer surfaces of which define the exterior of the vessel. Chambers 243 are provided both port and starboard in vessel 240. The chambers may be arranged so that exterior surfaces 244 thereof are essentially flush with the surfaces of hull 241 adjacent the chambers. On the other hand, chambers 243 may be defined within a specially strengthened ice belt structure which extends outwardly from hull 241 along the hull in a manner similar to the ice belts provided on the Manhattan as modified by Humble Oil & Refining Co. for the Northwest Passage exploratory voyages in 1969 and 1970.

Vessel 240 preferably is equipped with a turboelectric propulsion system which includes a gas turbine 245, only one of which is shown as representative of a plurality of turbines which normally would be provided. While it is not shown, the gas turbines are coupled to electric generators which in turn supply power to electric motors coupled to the propeller shafts of the vessel. The generators also provide power for operating motors coupled to air pressurizing mechanisms 246 and 247 provided forward and aft in the vessel in association with pitching chambers 28 and 29, respectively. As represented schematically in FIG. 21, the exhaust gases

from turbine 245 are led via a suitable exhaust duct 248 into a chambers 243. The turbine exhaust gases are extracted from chambers 243 adjacent the forward and aft ends of the chambers to travel by paths 249 and 250, respectively, to the inlets of air pressurizing mechanisms 246 and 247, respectively. At the inlets to the pressurizing mechanisms, the turbine exhaust gases are mixed with ambient air to provide the volume of air required to effectively operate pitching chambers 28 and 29; it is expected that the volume of exhaust gases from the turbines may not be adequate to meet the air requirements for induced pitching of vessel 240.

When an icebreaking vessel according to this invention is equipped in the manner illustrated in FIG. 21, the exhaust gases from turbine 245 may enter chambers 243 at a temperature of about 1,200° F. These gases may be withdrawn from the chambers adjacent their forward and aft ends at a temperature well above ambient temperature so that, when the gases are mixed with ambient air and introduced to the air pressurizing mechanisms, the air applied to pitching chambers 28 and 29 is substantially above ambient temperature. The air admitted to pitching chambers 28 and 29 to discharge water from the chambers is substantially above the freezing temperature of water. This fact assures that those portions of the structure of the pitching mechanisms subject to variable immersion during operation will not become coated with ice or jammed with ice. Also, the high temperature exhaust gases flowing through chambers 43 provide all the advantages described above concerning the heating mechanisms of icebreaking vessel 190. Additionally, the arrangement illustrated in FIG. 21 is thermodynamically efficient and derives maximum utilization from the energy content in the fuel used to power gas turbines 245.

The turboelectric propulsion system described for vessel 240 is further desirable since all or a desired fraction of the electrical power available on the vessel can be applied either to the vessel propulsion system or to the pitching system as desired, depending upon whether the vessel is operating in open water or in icebreaking operations.

Another icebreaking vessel 260 is shown in FIG. 22 and is similar to icebreaking vessel 240, shown FIG. 21 and described above; to the extent vessels 240 and 260 are alike, common reference numerals are used in FIGS. 21 and 22. Like vessel 240, vessel 260 includes a gas turbine, for the reasons already mentioned, which has its exhaust applied to each of a pair of air circulating chambers 243' provided port and starboard of hull 241. Chambers 243' extend longitudinally of the hull and have their outer surfaces arranged to define the exterior of the vessel. Also, as in vessel 240, gas applied to chambers 243' is supplied from each of the chambers to forward and aft pitching chambers 28 and 29, respectively.

Vessel 260 differs from vessel 240 in that a gas compressor is disposed between turbine 245 and chambers 243' to receive the exhaust gases from turbine 245 via duct 262. Preferably, compressor 261 and duct 262 are arranged so that ambient air is mixed with the turbine exhaust gases at the inlet to the compressor. The discharge from the compressor is supplied via a duct 263 to each of chambers 243' preferably intermediate the length of each of the chambers. Accordingly, a mixture of ambient air and turbine exhaust gases is supplied at elevated temperature and pressure to each of chambers

243' so that each of the chambers functions as an element of a hull heating system for the reasons mentioned above, and also as an accumulator in a pneumatically operated pitch-inducing system for vessel 260.

Pressurized gas, i.e., a mixture of air and turbine exhaust gases, is supplied from chambers 243' to each of pitching chambers 28 and 29, preferably from the forward and aft ends of the chambers respectively. Thus, the forward ends of chambers 243' are selectively connected to forward pitching chamber 28 via a suitable duct 264 and a gas flow control valve 266. Similarly, the aft ends of chambers 243' are connected to aft pitching chamber 29 via gas flow duct 265 and selectively operable gas flow control valve 267. The operation of valves 266 and 267 is controlled by control device 47 which is arranged so that gas at elevated pressure is applied to the forward and aft pitching chambers at intervals which are 180° out of phase with each other, as described above, to induce high amplitude pitching of vessel 260 at intervals which correspond to the natural icebreaking pitch period of the vessel.

It is apparent that vessel 260 provides the advantages described above for vessel 240 in addition to the advantages specifically described above for vessel 260.

It is emphasized that this invention contemplates that pitching chambers may be provided both fore and aft in a vessel according to this invention, or either forward or aft, as desired. Accordingly, the fact that FIGS. 3, 4, 5, 6, 7, 8, 9, 10 and 11 depict only a single pitching chamber should not be taken to mean that the induced pitching systems depicted in these figures necessarily incorporate only a single pitching chamber.

It was noted briefly above that the induced pitching mechanisms which have been described are essentially massless in character in that they do not rely upon the addition of mass to the icebreaking vessel to produce the desired pitching motions, nor do they rely upon a transfer of mass within the hull of the vessel. Internal mass transfer pitching systems inherently have to operate against the types of motions they are relied upon to produce. For example, where water ballast is shifted fore and aft internally of the vessel, it is necessary to pump the ballast uphill to reverse the trim condition of the vessel to generate pitching; this is true unless the phase lag angle between the ballast transfer system and hull motion is 180°. The buoyancy-oriented pitching mechanisms described herein, however, act rapidly upon the vessel and also may be removed rapidly from the vessel. Because the present pitching systems are massless in nature, they are not subject to the objections of momentum and vibration which characterize internal mass transfer systems of the type described by Waas, for example.

In the foregoing description, reference has been made to specific procedures and structural arrangements which have been selected for the purpose of example in furtherance of a clear and comprehensive presentation of this invention in compliance with pertinent statutes. Workers skilled in the art to which this invention pertains will readily recognize that the specific procedures and structural arrangements described above may be altered or modified without departing from the scope of the invention, which scope should be clear from the several embodiments described in detail. Accordingly, the foregoing description should not be considered as limiting the scope of this invention.

What is claimed is:

1. An improved vessel for use in ice-covered waters comprising

a. a hull having

1. a bow portion of icebreaking configuration and

2. a pitching chamber therein spaced along the hull from the longitudinal center of buoyancy thereof and communicable through the hull below the waterline,

b. means selectively operable for cyclically applying compressed air to the chamber essentially directly to water therein for rapidly displacing water substantially completely therefrom and for rapidly admitting water to the chamber thereby to directly shift the position of the center of buoyancy along the vessel without change in the location of the vessel center of gravity to produce cyclic pitching movements of the hull, which cyclic motions have a period measured in terms of several seconds and an amplitude of at least a foot measured at the ends of the hull, and

c. means for operating the selectively operable means at a selectable frequency within a range of frequencies each of which has a period of several seconds.

2. A vessel according to claim 1 wherein the pitching chamber is provided as a recess defined in the bottom of the hull.

3. A vessel according to claim 1 wherein the pitching chamber is located forward of the hull center of buoyancy.

4. A vessel according to claim 3 including a second pitching chamber similar to the forward pitching chamber and located aft of the hull center of buoyancy, selectively operable means for the second pitching chamber and means for operating the same in a reverse phase relation to the selectively operable means for the forward pitching chamber.

5. A vessel according to claim 1 wherein the selectively operable means includes a source of pressurized air, air supply and exhaust duct means connected to the chamber, and air flow control means associated with the duct means operable between a first state in which air is supplied by the duct means to the chamber and a second state in which air is exhausted by the duct means from the chamber.

6. A vessel according to claim 5 wherein the duct means includes separate supply and exhaust duct means connected to the chamber.

7. A vessel according to claim 6 wherein the source of pressurized air comprises the compressor stage of a gas turbine engine.

8. A vessel according to claim 5 wherein the source of pressurized air is adapted for non-intermittent operation, and venturi means associated with the duct means for operation by air from the source for evacuating air from the chamber when the flow control means is in its second state.

9. A vessel according to claim 6 wherein the chamber is disposed within the hull and the exhaust duct means effectively communicates from the chamber through a submerged location of the hull.

10. A vessel according to claim 1 including means for directing air-displaced water from the chamber substantially athwartships of the vessel.

11. A vessel according to claim 10 wherein the chamber is disposed adjacent the bow of the vessel.

12. A vessel according to claim 1 wherein the hull bow portion is configured to engage the underside of a floating ice sheet during upward excursions of the bow and to engage the upper side of the ice sheet during downward excursions of the bow.

13. A vessel according to claim 12 wherein the bow is raked upwardly and forwardly from substantially the even-keel waterline and is raked downwardly and forwardly from substantially said waterline.

14. A vessel according to claim 1 including ice-engaging projection means extending fixedly laterally from the hull and from adjacent the bow for a selected distance toward the stern.

15. A vessel according to claim 14 wherein the projection means has a warped ice-engaging surface opening generally downwardly and curved along its extent to face more outwardly from the hull at its aft end than at its forward end.

16. A vessel according to claim 15 wherein said surface of the projection means is continuously curved along its length.

17. A vessel according to claim 14 wherein the projection means are arranged, during downward movement of the bow in response to operation of the selectively operable means, to apply force to ice adjacent the hull progressively from the aft end of the projection means to the forward end thereof.

18. A vessel according to claim 17 wherein the projection means is configured so that engagement of the projection means with ice adjacent the hull during application of said force moves substantially continuously toward the bow.

19. A vessel according to claim 1 including means operatively coupled to the hull adjacent the bow and for a selected distance aft therefrom for heating the hull external surface in a selected area thereof sufficient to prevent bonding of ice to the hull.

20. A vessel according to claim 19 wherein said selected area corresponds to the forward hull area subject to variable immersion in response to operation of the selectively operable means.

21. A vessel according to claim 19 wherein the vessel includes a gas turbine, a chamber extending along the hull on each side thereof arranged so that the outboard boundaries of the chambers comprise the selected area, and means for supplying the turbine exhaust gases to the chambers.

22. A vessel according to claim 21 including means for supplying turbine exhaust gases from the hull heating chambers to the selectively operable means.

23. A vessel according to claim 1 including means for operating the selectively operable means to induce cyclic heaving of the hull.

24. A vessel according to claim 1 including forcing surface means carried by the vessel and extending along at least a portion of the length thereof for applying displacing force to matter adjacent the hull in response to induced downward movements of the hull, the forcing surface means extending outwardly and at least partially upwardly from the hull proximate the operative waterline thereof.

25. An improved vessel for use in ice-covered waters comprising

- a. a hull having a bow portion of icebreaking configuration,
- b. a pneumatically operated means including a pitching chamber adjacent the bow effectively commu-

nicating through the hull below the waterline and operable for cyclically altering the effective configuration of the hull to produce a movement of the hull center of buoyancy along the length of the hull without change in the location of the vessel center of gravity, thereby to produce low frequency, high amplitude cyclic pitching movements of the hull, which cyclic movements have a period measured in terms of several seconds and an amplitude of at least a foot, the pneumatically operated means also including means for conducting air to and from the chamber for varying the volume of water effectively contained in the chamber, and

- c. means for operating the pneumatically operated means at a selectable frequency within a range of frequencies each of which has a period of several seconds.

26. An improved vessel for use in ice-covered waters comprising

- a. a hull having a bow portion of icebreaking configuration, and
- b. at least principally pneumatically operated means operatively associated with the hull and operable at a selectable frequency within a range of frequencies each having a period measured in terms of several seconds for shifting the hull center of buoyancy fore-and-aft at said frequency without significantly altering the location of the center of gravity thereof, thereby to produce cyclic pitching motions of the hull with a period measured in terms of several seconds and an amplitude of at least a foot, the pneumatically operated means including a chamber in the hull spaced along the length thereof from the center of buoyancy thereof in effective communication through the hull below the waterline and means for conducting air to and from the chamber for varying the volume of water effectively in the chamber.

27. An improved vessel for use in ice-covered waters comprising

- a. a hull having
 1. a bow portion of icebreaking configuration and
 2. a pitching chamber therein defined as wing tank means spaced along the hull from the longitudinal center of buoyancy thereof, the wing tank means extending from proximate the bow for a selected distance aft along the hull,
- b. means selectively operable for applying air to the chamber for displacing water therefrom and for admitting water to the chamber thereby to induce motion of the hull, said means including
 1. controllable means for admitting pressurized air to the upper extent of the wing tank means and for venting air from the wing tank means at the upper extent thereof,
 2. means in the outer walls of the wing tank means for discharging water from the wing tank means substantially laterally outwardly from the vessel, which means include
 - i. a plurality of jet nozzles mounted in the outer walls of the wing tank means, and
 - ii. means associated with at least some of the jet nozzles for rendering the nozzles operative only when the nozzles are located below the surface of water in the wing tank means, and

- 3. means in the lower extent of the wing tank means for admitting water to the wing tank means, and
- c. means for operating the selectively operable means at a selectable frequency which corresponds to the optimum motion energy transfer characteristic existing between the hull and its proximate surroundings.
- 28. An improved vessel for use in ice-covered waters comprising
 - a. a hull having
 - 1. a bow portion of icebreaking configuration, and
 - 2. a pitching chamber therein spaced along the hull from the longitudinal center of bouyancy thereof and communicable through the hull below the waterline, the chamber being defined as wing-tank means extending from proximate the bow for a selected distance aft along the hull and from adjacent the keel to adjacent the gunwale,
 - b. means selectively operable for cyclically applying compressed air to the chamber essentially directly to water therein for rapidly displacing water substantially completely therefrom and for rapidly admitting water to the chamber thereby to directly shift the position of the center of buoyancy along

- the vessel without change in the location of the vessel center of gravity to produce low frequency, high amplitude pitching of the hull, and
- c. means for operating the selectively operable means at a selectable frequency which is correlated to the optimum pitch energy transfer characteristic existing between the hull and its proximate surroundings.
- 29. A vessel according to claim 28 wherein the selectively operable means includes controllable means for admitting pressurized air to the upper extent of the wing tank means and for venting air from the wing tank means at the upper extent thereof, means in the outer walls of the wing tank means for discharging water from the wing tank means substantially laterally outwardly from the vessel, and closable means in the lower extent of the wing tank means for admitting water to the wing tank means.
- 30. A vessel according to claim 29 wherein the water discharging means includes a plurality of jet nozzles mounted in the outer walls of the wing tank means.
- 31. A vessel according to claim 30 wherein the jet nozzles are arranged in a selected pattern extending vertically and longitudinally of the wing tank means.

* * * * *

30

35

40

45

50

55

60

65