Australian Government
IP Australia

LETTERS PATENT

STANDARD PATENT

2002309688

I, David Johnson, the Acting Commissioner of Patents, grant a Standard Patent with the following particulars:

Name and Address of Patentee(s):

Thomas G Lang
417 Loma Larga Drive, Salona Beach, CA, 92075, United States of America
James T Lang
417 Loma Larga Drive, Salona Beach, CA, 92075, United States of America

Name of Actual Inventor(s):

Lang, Thomas, G. and Lang, James, T..

Title of Invention:

Low-drag hydrodynamic surfaces

Term of Letters Patent:

Twenty years from 10 May 2002

Priority Details :

Number	***Date***	***Filed with***
09/852,616	11 May 2001	US

Dated this 28th day of August 2008

David Johnson
Acting Commissioner of Patents

PATENTS ACT 1990

(12) STANDARD PATENT (11) Application No. **AU 2002309688 B2**
(19) AUSTRALIAN PATENT OFFICE

(54) Title
Low-drag hydrodynamic surfaces

(51) International Patent Classification(s)
B63B 1/24 (2006.01) *B63B 1/38* (2006.01)

(21) Application No: **2002309688** (22) Date of Filing: **2002.05.10**

(87) WIPO No: **WO02/092420**

(30) Priority Data

(31) Number	(32) Date	(33) Country
09/852,616	**2001.05.11**	**US**

(43) Publication Date: **2002.11.25**
(43) Publication Journal Date: **2003.05.01**
(44) Accepted Journal Date: **2008.05.15**

(71) Applicant(s)
Thomas Lang;James Lang

(72) Inventor(s)
Lang, Thomas, G.;Lang, James, T.

(74) Agent / Attorney
Fisher Adams Kelly, Level 29 Comalco Place 12 Creek Street, Brisbane, QLD, 4000

(56) Related Art
US 6167829

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
21 November 2002 (21.11.2002)

PCT

(10) International Publication Number
WO 02/092420 A1

(51) International Patent Classification⁷: **B63B 1/24**

(21) International Application Number: PCT/US02/14652

(22) International Filing Date: 10 May 2002 (10.05.2002)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
09/852,616 11 May 2001 (11.05.2001) US

(71) Applicants and
(72) Inventors: LANG, Thomas, G. [US/US]; 417 Loma Larga Drive, Salona Beach, CA 92075 (US). **LANG, James, T.** [US/US]; 417 Loma Larga Drive, Salona Beach, CA 92075 (US).

(74) Agents: WRAY, James, C. et al.; Suite 300, 1493 Chain Bridge Road, McLean, VA 22101 (US).

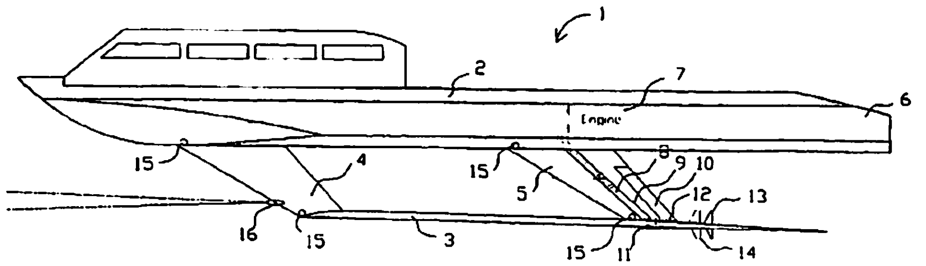
(81) Designated States *(national)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZM, ZW.

(84) Designated States *(regional)*: ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report*
— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: LOW-DRAG HYDRODYNAMIC SURFACES



(57) Abstract: The invention relates to the use of gas cavities (32, 33) to reduce frictional drag on underwater surfaces such as hydrofoils, struts, fins, rudders, keels, propeller blades, ship hulls, underwater bodies, and wetted surfaces in general. Each gas-filled cavity is formed behind a discontinuity (31A, 31B) in the surface (34, 35) that causes the water boundary layer to separate from the surface. Gas is ejected into a region behind the discontinuity to fill the cavity; the gas can be air. If the cavity is open to the atmosphere, then air can typically fill the cavity naturally without air ejection. Cavities can either be closed or open. A low drag hydrofoil may have a closed cavity on one side, and an open cavity on the other side. For closed cavities, the underlying surface can be shaped to minimize cavity closure drag.

WO 02/092420 A1

Low-Drag Hydrodynamic Surfaces

This invention was made with Government support under DAAH01-96-C-R228, and DAAH01-98-C-R115 awarded by the Defense Advanced Research Projects Agency. The Government has certain rights in this invention.

BACKGROUND OF THE INVENTION

This invention applies to the field of hydrodynamics, and relates to the use of gas cavities to reduce the frictional drag of hydrofoil craft, ship hulls and underwater surfaces in general.

Using cavities to reduce frictional drag is covered in U.S. Pats. No. 3,077,173 (1963) and No. 3,109,495 (1963) for base-vented and side-vented hydrofoils, U.S. Pat. No. 3,205,846 (1965) for torpedoes, and U.S. Pat. No. 6,167,829 (2001), together with a pending continuation of that patent, for submerged surfaces in general.

The reduction of frictional drag provides basic benefits: power is reduced, and fuel consumption is reduced. These benefits reduce the weight of a vessel, which further reduces power and fuel consumption compared with a fully wetted vessel designed for a given payload and range. Alternatively, vessel speed can be significantly increased with the same displacement, power, payload and range. Cost and time for payload delivery are greatly reduced by reducing drag.

The problem is how to design underwater surfaces to make full use of cavities to reduce drag. Needs exist for improved drag reduction in water craft.

SUMMARY OF THE INVENTION

A primary objective of this invention is to reduce the drag of high-speed hydrofoil craft by forming a closed gas cavity on each side of each lifting hydrofoil, forming an open cavity on each side of each support strut, and by covering at least one side of each propulsor blade with a cavity.

A preferred design is a hydrofoil craft that has one highly-swept-back v-hydrofoil in planform, supported by three swept struts, powered by two superventilating propellers wherein each drive shaft is located within a strut, and wherein the hydrofoil sweep back eliminates cavitation and reduces craft motion in waves.

Another objective is to efficiently control the lift of hydrofoil cross sections having closed cavities by using trailing edge flaps, optional leading edge flaps, and optional means for controlling gas flow rates.

Other objectives are to efficiently initiate cavities by introducing discontinuities to separate the water boundary layer in various ways, efficiently distribute the gas to each cavity, control the cavities, and separate adjacent cavities with different kinds of fences.

Still another objective is to minimize cavity drag on underwater surfaces by closing the cavities as smoothly as possible by minimizing the contact angle between the cavity and the surface. Another objective is to further minimize cavity drag by adding parallel ridges in the vicinity of cavity closure to reduce forward splash and thereby minimize gas entrainment out of the cavity.

Yet another objective is to use cavities to reduce the drag on all sides of ship hulls. Further objectives are covered in the description which includes the above and ongoing specification and claims.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic representation of the side view of a low-drag, high-speed hydrofoil craft showing an above-water hull, a hydrofoil, support struts and a propeller.

Figure 2 shows a bottom view of the craft.

Figure 3 is a front view of the craft.

Figure 4 is a front view of a similar craft powered by shrouded air propellers.

Figure 5 illustrates a hydrofoil with reverse sweep from that shown in Figure 2.

Figure 6 is a schematic cross section of a low drag hydrofoil with a tail flap, showing a cavity sensor, and two alternative closed cavities on each surface: a design cavity, and a slightly longer cavity.

Figure 7 shows the same hydrofoil with the flap deflected.

Figure 8 is a schematic detail of an alternative hydrofoil nose section comprising an angled plate.

Figure 9 is a schematic detail of another alternative hydrofoil nose section comprising a perpendicular plate.

Figure 10 is a schematic representation of a different kind of low drag hydrofoil that has a closed cavity on the upper surface, and a superventilated cavity on the lower surface.

Figure 10B is a schematic representation of a different way to control hydrofoil lift by forming a superventilated cavity on either the lower surface of a low drag hydrofoil, as shown in Fig. 10, or by forming a similar superventilated cavity on the upper surface.

Figure 11 is a schematic detail of a wedge-shaped hydrofoil nose section with variable wedge angles.

Figure 12 is a schematic detail of an alternative wedge-shaped hydrofoil nose section having a sliding block at each aft end to control cavity thicknesses.

Figure 13 is a schematic detail of an angled-plate hydrofoil nose section with a variable plate angle.

Figure 14 is a cross section of a nose region of a hydrofoil showing a means to duct gas from a cavity on one side into a cavity on the other side.

Figure 15 is a cross section of a nose region of a hydrofoil showing flaps that cover gas ejection holes or slots.

Figure 16 is a cross section at a strut-hydrofoil juncture showing how gas is delivered to different internal chambers in a hydrofoil.

Figure 17 is a cross section of a hydrofoil showing methods for initiating cavities, moving gas from internal chambers into the cavities, removing gas from cavities, and for recycling the removed gas.

Figure 18 is a similar cross section showing different ways to duct gas from a strut into internal ducts in a hydrofoil, and to move gas between different internal ducts within the hydrofoil.

Figure 19 is a cross section of a hydrofoil showing how gas can be moved from several ducts in a strut into several ducts in a hydrofoil.

Figure 20 is a schematic detail of a tail region of a hydrofoil showing a tab in a tail flap.

Figures 21A and B illustrate parallel ridges on a hydrofoil surface aligned with the water flow that are located in the desired cavity closure region.

Figure 22 is a spanwise cross section of a hydrofoil surface showing four kinds of fences that can be used to separate adjacent gas cavities.

Figures 23A and B are side and end views of a swept, tapered strut that supports a hydrofoil, showing an upper superventilated region, a fence, a lower strut region with a closed cavity, and a bottom region that is fully wetted.

Figure 24 is a cross section of the strut showing an optional nose flap used to deflect a cavity, a trailing edge flap, different internal ducts, and optional side wedges.

Figure 25 is a schematic detail of a nose section of a strut showing how cavities are initiated, and how a nosepiece can be attached to the strut body.

Figure 26 illustrates an alternative flat plate nose to initiate cavities.

Figure 27 illustrates an elongated version of the nosepiece shown in Figure 25.

Figure 28 is a side view of a strut that is swept down and forward.

Figure 29 is a front view of an angled strut.

Figure 30 is a cross section of a strut showing how a bottom portion of the strut, and an attached hydrofoil, can be spring loaded to reduce craft motion.

Figure 31 shows a propeller hub with a cross section of a superventilating propeller blade.

Figure 32 is a similar view showing a propeller blade that has a closed gas cavity on its suction side, and an open, superventilated cavity on its lower side.

Figure 33 is a similar view showing a propeller blade that has a closed gas cavity on each side.

Figure 34 is a cross section of a pod that encloses an electric motor which drives a shrouded propeller.

Figure 35 is a side view of a hydrofoil boat hull supported above water by struts attached to a primary swept v-hydrofoil, together with a bow lifting device comprising an inverted, swept v-foil that provides pitch and roll stability.

Figure 36 is a front view of the boat.

Figure 37 is a side view of an alternative bow lifting device comprising parallel, flexible planing plates.

Figure 38 is a front view of an alternative primary v-hydrofoil wherein the ends of the hydrofoil are canted upward to pierce the water surface to provide roll stability.

Figure 39 is a front view of the main hydrofoil wherein the aft support struts are angled to provide roll stability, and the bow lifting device is a surface piercing v-hydrofoil in front view.

Figure 40 is a side view of the hydrofoil boat wherein the main v-hydrofoil is reversed in sweep wherein the tips of the hydrofoil are forward, and are canted upward to provide pitch and roll stability.

Figure 41 is a side view of a hydrofoil boat hull supported above water by a strut attached to a lifting, swept v-hydrofoil, wherein part of the boat lift is provided by aerodynamic wing lift, and wherein the boat is stabilized in pitch and yaw by an aerodynamic tail.

Figure 42 is a side view of a ship hull showing multiple closed cavities on side and bottom surfaces.

Figure 43 is a horizontal cross section of the ship hull showing the side cavities.

Figure 44 is a side view of a ship hull that is mostly submerged, and has closed cavities on the side, bottom and top surfaces.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

In Figures 1 and 2, the hull 2 of hydrofoil craft 1 is supported above water by forward strut 4 and two aft struts 5 which are attached to lifting v-hydrofoil 3. The propulsion system consists of engine 7 in each catamaran hull 6 that drives shaft 8 located in duct 9 of strut 5, thereby eliminating drag on the drive shaft. Shaft 8 enters gearbox 11 located inside pod 12 to drive propeller 13. Pre-spin vanes 14 rotate the water flow entering the propeller so that the water flow leaves the propeller without significant rotation, thereby increasing propeller efficiency. This hydrofoil and propulsion arrangement is equally applicable to monohulls, trimarans or other hull shapes, and applies to one or more support struts, engines and propulsors. Each strut can either be swept back, as shown, or unswept, or swept forward. Strut sweep reduces strut spray drag, and reduces strut side force in beam waves. Hydrofoil sweep reduces susceptibility to cavitation, and reduces craft vertical motion in waves. The sweep shown in Figure 2 is around 70 degrees. Sweep of only 30 degrees is beneficial. Sweeps of 45 and 60 degrees are more beneficial. These beneficial effects are not affected whether a hydrofoil is swept back or forward. With a leading edge sweep angle of 70 degrees, the included angle between leading edges is 40 degrees. With a sweep angle of 30 degrees, the included angle is 120 degrees. Sweep angles are measured from a direction perpendicular to the craft centerline. Hydrofoil chord distribution affects induced drag. Minimum induced drag occurs for an elliptic chord distribution. Longer chords are nearer the craft center, shorter chords are nearer the hydrofoil tips.

Rudder 10 in each aft strut 5 helps to steer the craft. Banking the craft into a turn by using flaps increases turn rate, and minimizes craft side force. Hinges 15 permit the hydrofoil to retract rearward and upward. Sonar device 16 helps to detect underwater obstacles that lie in the path of the craft, and can also serve to generate forward-projected sounds to frighten or urge sea animals away from the path of the craft.

Outboard trailing edge flaps 17 serve to control craft roll and pitch, and together with inboard flaps 18, serve to control craft height. Fences 19, wetted pods 12, and wetted region 20 serve as fences to separate adjacent spanwise cavities on the hydrofoil in the case where the hydrofoil is supplied with gas cavities to reduce drag. Projection 21 on the underside of hull 2 at the center helps to reduce forward strut height, and to cushion bow impacts when operating in large waves.

A sweptback v-hydrofoil that is placed at a small angle of attack can appear to have a small negative dihedral 22, or it can be designed for a negative dihedral; in either case, it will appear somewhat as shown in Figure 3. Alternatively, for dynamic reasons in some cases, a v-hydrofoil might be designed with a positive dihedral 23, as shown in Figure 4.

Calculations show that shrouded air propellers 24, such as shown in Figure 4, can be as efficient as underwater propellers in some cases.

Figure 5 illustrates a hydrofoil 25 whose sweep is reversed from that of hydrofoil 3 in Figure 2. From the viewpoint of foil sweep theory, little difference exists whether a foil is swept forward or back.

The drag of a hydrofoil, such as the one shown on the craft in Figures 1 and 2, can be greatly reduced by covering the majority of one or both surfaces with a closed gas cavity, as shown in Figure 6. The wedge-like nosepiece 31 of hydrofoil 30 introduces a surface discontinuity 31A on an otherwise streamlined upper surface 34, and a surface discontinuity 31B on an otherwise streamlined lower surface 34 of the hydrofoil, that causes the water boundary layer to separate from each side of the nosepiece. By introducing gas into the wake region of separated flow lying behind the discontinuity, a gas cavity 32, 33 can be formed. The flow discontinuity can be a 90-degree downward angle or step in the surface, as shown, or it could be a smaller downward angle, to as little as around 10 degrees. The discontinuity can also be a protuberance from the surface, such as spanwise wedge with a blunt trailing edge, where a trailing edge step serves to separate the water boundary layer from the surface. Other kinds of discontinuities are shown in Figures 12-14.

Theory shows that cavity drag is zero, if the cavity closes smoothly. In the real world, it is not possible to exactly smoothly close a cavity. However, it is possible to minimize the contact angle between a cavity and an underlying surface in the cavity closure region so that forward splash at cavity closure is minimized, thereby minimizing the gas entrainment rate, and thus minimizing the size of the wake, and cavity drag.

Figure 6 shows two cavities on each hydrofoil surface 34, 35, a shorter cavity 32S, 33S that closes in desired closure regions 36 and 37, and a longer cavity 32L, 33L that closes at 38 and 39 behind the desired closure region. Note that the hydrofoil surface 34, 35 is convexly curved so that the closure angle of shorter cavity in each case is much smaller than the closure angle of the larger cavity. Because of the greater closure angle, more gas is entrained out of the larger cavities than out of the shorter cavities. Consequently, if the gas flow rate into each cavity is controlled so as to not exceed the rate needed to close the shorter cavity, then neither cavity can close behind the desired closure region because not enough gas will be available to further extend the cavity. To determine where a cavity closes, cavity sensors 40 can be used to sense cavity length.

The shape of a gas cavity depends upon the cavity number $K=(Po-Pc)/q$, where Po is static depth pressure, Pc is cavity pressure, and q is the dynamic water pressure, where q is the speed squared times half the mass density of water. If K is small, the cavity is long and thin, and if K is large, the cavity is short and thick. In two-dimensional flow, $K=2T/C$ where T=cavity thickness and C= cavity length; the cavity shape is an ellipse. As used throughout this patent, the word "gas" means any kind of gas, including air.

A tail flap 29 is shown in Figure 6 in its neutral position, and is shown deflected in Figure 7. Note that the location of the closure points, 42 and 43, for the longer cavity on each surface has not appreciably changed, indicating that the flap can be deflected without risk of the longer cavities lengthening beyond the trailing edge, especially if the flap is long enough. If necessary, a flap chord can be increased when the flap is deflected. Placing a concave surface just ahead of the trailing edge on each side of the flap will increase the cavity closure angle in the region ahead of the trailing edge to help to ensure that the longer cavities will not close behind the trailing edge.

A variety of nosepiece shapes can be used to initiate the cavities, such as angled nosepiece 44 placed on the lower front side of the hydrofoil in Figure 8 to start cavities at discontinuities 45 and 46, or nosepiece 47 placed perpendicular to the flow in Figure 9. Such nosepieces can be placed at any angle greater than about five degrees to the oncoming water flow. The nosepiece can be curved either way, and can include changes in angle. Nosepiece 47 can instead be v-shaped, or cup-shaped, wherein the upper and lower edges lie ahead of the center section.

The special hydrofoil shape in Figure 10 shows promise for even-greater frictional drag reduction because its only wetted surface areas are the lower surface of the nosepiece 44 and the upper surface of the trailing edge flap. Here, the upper surface is covered with closed cavity 32, and the lower surface is covered with an open, superventilated cavity 48. The two cavities close behind the trailing edge at 49. This hydrofoil design should have very low frictional drag if the cavity merger angle at 49 is made small.

An alternative method for controlling hydrofoil lift is shown in Fig. 10B. A large change in lift occurs whenever a closed cavity is changed into a superventilated cavity. By sufficiently increasing the gas flow rate into closed cavity 33 on hydrofoil 30, the cavity will change into superventilated cavity 33A and hydrofoil lift will greatly increase. Similarly, by sufficiently increasing the gas flow rate into closed cavity 34 on the upper surface of hydrofoil 30, the cavity will change into superventilated cavity 32A and the lift will greatly reduce.

Experiments conducted by the inventors show that the upper and lower cavities remain closed over specific ranges of gas flow rates; each such range is called the design gas flow range for that surface. If the gas flow rate is increased above the design range for a surface, then that cavity begins to intermittently fluctuate back and forth between a closed cavity and a superventilated cavity. As the gas flow rate increases above the design range, the fraction of time spent in the superventilated cavity mode increases from 0% to 100%; this fraction was found to be roughly proportional to gas flow rate. This gas flow range is called the transition gas flow range. Alternatively, if the gas flow rate is suddenly increased above the transition gas flow range, then a closed cavity suddenly transforms into a steady superventilated cavity.

Consequently, controlling gas flow rate within the transition range provides continuous control over hydrofoil lift, somewhat similar to controlling flap angle to control hydrofoil lift. Alternatively, if the gas flow rate is suddenly increased to above the transition gas flow range, then a closed cavity will suddenly change into a superventilated cavity. This latter method is sometimes called a "bang-bang" control system wherein the fraction of time spent in the superventilated mode determines the lift change.

If a given region of a hydrofoil span is to be controlled by gas flow rate, and an adjacent region is either be not controlled or be controlled independently, then a fence must be placed between the two regions. Such a fence can be similar to fences used with a flap control system, for example fence 19 or wetted pod 12 shown in Fig. 2, or the various alternative fences shown in Fig. 22 in end view.

The concept of controlling hydrofoil force by controlling gas flow rate can be equally well applied to controlling forces on other kinds of hydrofoils such as struts, fins, rudders, and blades of propulsors and propellers. In general, this concept can be used to control forces on almost any submerged surface that is convexly shaped in the flow direction, including hulls of either surface or subsurface vehicles or bodies.

Any description made in this patent referring to gas or gas flow is meant to refer equally well to air and airflow.

The shape of a wetted hydrofoil nosepiece can be varied to change upper and lower cavity shapes, assist in controlling lift, and to reduce drag. For example, the angles of the upper and lower surfaces of wedge-shaped, flexible plate 58 can be independently controlled, as shown in Figure 11, by changing the length of actuator 60 which is attached between rigid hydrofoil center plate 55 and rigid nose plate

59 to deflect the flexible v-plates 56 and 58 either outward or inward. The lower part 57 of the nosepiece can be controlled similarly.

Another way to change nosepiece shape is shown in Figure 12 where plate 61 is moved vertically relative to nosepiece 31 in order to deflect cavity 32.

Still another way to change nosepiece shape is shown in Figure 13 where plate 44 is rotated about axis 62 to deflect upper and lower cavities 32 and 33.

Because cavity number K increases as speed reduces, cavities tend to be shorter and thicker at lower speeds. Therefore, to reduce frictional drag at lower speeds, it is necessary to change cavity shape by either changing hydrofoil geometry, hydrofoil angle of attack, gas flow rates, cavity pressures, or combinations thereof. Various ways of changing hydrofoil geometry and hydrofoil pitch or angle of attack have been discussed. Typically, for a given hydrofoil geometry, a change in gas flow rate will provide an accompanying change in cavity pressure and shape. Thus, the gas source pressures and flow rates must be adequate to supply gas to the cavities under all of the desired operating conditions.

In most hydrofoil designs, the cavity pressure on the upper surface is less than atmospheric pressure, in which case the upper cavity gas can be air that is drawn from the atmosphere without using an air pump. If the upper cavity pressure is low enough, then a turbine can be placed in the associated air duct to generate power. Typically, the pressure on the lower surface of a hydrofoil is greater than atmospheric, in which case the gas, such as air, must be pressurized using a pump. However, in some cases, hydrofoil speed and geometry is such that the pressure on the lower surface of a hydrofoil, although greater than the pressure on the upper surface, can be made less than atmospheric pressure, in which case, no pump is needed and atmospheric air can be used.

For all lifting hydrofoils, the lower cavity must be at a higher pressure than the upper cavity. Consequently, there may be design cases where the simplest and best solution is to supply gas only to the lower cavity, and then duct some of the gas into the upper cavity. One such way is shown in Figure 14 where gas from a lower cavity is passed through duct 63 to an upper cavity using orifices 64 and/or 65 to meter, or restrict, the gas flow rate. These orifices, restrictors, or limiters could be valves, or ducts 63 could be made small enough to act as a restrictor, or limiter, to meter the gas flow rate without using valves or orifices.

It may be desirable to keep water out of the hydrofoil gas ducts. Figure 15 shows flaps 68 that are used to cover gas ejection holes, or gas releasers, from hydrofoil ducts 69 and 70 through upper hydrofoil plate 66, and lower hydrofoil plate 67, wherein the flaps close the holes when no gas is ejected, but spring open when gas is released. Alternatively, one-way valves can be used instead of flaps.

In some cases, it is desirable to replace nosepieces, including the case where a nosepiece is damaged. The various kinds of nosepieces shown in Figures 11-14 can be attached by various well-known methods to permit them to be removable.

Figure 16 shows how gas enters hydrofoil ducts 69 and 70 from strut ducts 71 and 73, which act as gas sources, at a strut/hydrofoil juncture. Ducts 71 and 73 are more typically placed one ahead of the other in the plane of the strut rather than as side-by-side, as shown for clarity in the figure.

The hydrofoil cross section in Figure 17 again shows strut ducts 71 and 73 to bring gas into hydrofoil duct 69 for ejection into upper surface cavities, and into duct 70 for ejection into lower surface cavities. In this case, valves or holes 78 and 79 meter some of the gas into adjacent spanwise ducts for distribution to other cavities located at other spanwise stations along the hydrofoil span. The gas passes through restrictor permeable walls 72 and 74 at the forward ends of the hydrofoil ducts, through slots at the front end of the upper and lower hydrofoil plates, and into the upper and lower cavities. The upper and lower surfaces of the hydrofoil are said to be substantially, or essentially, continuous in spite of the small slot aft of the nosepiece through which gas is ejected. To provide greater strength, if needed, the hydrofoil can be made solid in the mid and aft section, as shown in Figure 17. If it is desired to remove gas from a hydrofoil cavity on one or both sides, and recycle it, then a suction inlet and gas pump, such as 75, 76, can be installed where the gas is returned by line 77 to gas duct 69 for recycling.

Another way to distribute gas to different cavities located on the upper and lower surfaces of a hydrofoil is shown in Figure 18. Gas for the upper surface cavities enters from strut duct 71 into hydrofoil duct 80 where it passes through valves 82 into separated forward spanwise ducts 69, and from there through restrictor holes in wall 72 into separated spanwise cavities located along the upper surface of the hydrofoil. Gas for the lower surface cavities enters from strut duct 73 into hydrofoil duct 83 where it passes through valves 85 into separated rearward and forward spanwise ducts 86, 70, and through holes in walls 87 and 74 into separated spanwise cavities located along the lower surface of the hydrofoil.

Still another way to distribute gas into cavities is shown in Figure 19. Gas for one upper surface cavity enters from duct 71 into an upper hydrofoil duct where it passes forward through holes in wall 72 into the cavity, while gas for a second upper surface cavity enters from duct 90 into a different upper hydrofoil duct where it passes forward through different holes in walls 92 and 72, while gas for a third upper surface cavity enters from duct 94 into a still different upper hydrofoil duct where it passes forward through still different holes in walls 96, 92 and 72. Each of the three hydrofoil ducts is sealed spanwise to prevent gas from being ejected into more than one cavity. Similarly, gas for the lower surface cavities enters the hydrofoil through ducts 73, 91 and 95, and passes through different holes in walls 74, 93 and 97.

As seen from Figures 14, 15, and 17-19, many different ways, and combinations of ways, exist for gas to be moved from strut ducts into hydrofoil cavities.

To reduce the torque needed to deflect a tail flap, such as flap 39 in Figure 20, a section of the flap, such as tab 100, can be pivoted about axis 101.

As mentioned earlier, some cavity drag will occur at cavity closure due to forward splash and air entrainment. To minimize cavity drag, small parallel ridges 105, as shown in side view in Figure 21A, and as shown in cross sections A-A in Figure 21B, can be placed in line with the water flow in the region of cavity closure to reduce splash and air entrainment. The ridges serve to direct the splash sideward and rearward, instead of directly forward, thus reducing disturbances at cavity closure, and thereby reducing air entrainment and drag. The ridges can be saw-shaped as in 106, or u-shaped as in 107, but should be aligned to within 30 degrees with the local water flow direction. Other ridge shape cross sections can be used, and the height of the ridges can taper down at each end.

Whenever gas cavities are formed on hydrofoils, struts or other surfaces, the pressures in adjacent cavities can be different, in which case the cavities should be separated by some type of a fence. Figure 22 shows four types of fences, looking in the direction of water flow. Fence 110 is a wetted region on the underwater surface, and if sufficiently wide, serves to separate adjacent cavities having different pressures. A more common type of fence is thin plate 111 whose height must exceed the cavity height, and whose length must exceed the cavity length. Still another type of fence is water jet 112 comprising a sheet of water directed outward from the surface that has sufficient momentum to reach the cavity walls before being curved away from the cavity walls due to the pressure difference between cavities. Another type of fence is gas jet 113, which is similar to the water jet fence in that it also requires sufficient momentum to reach the cavity walls before being curved away from the cavity walls.

Strut 120, shown in Figure 23A and B, is superventilated 117 in an upper region 118 of the strut on both sides down to fence 124, starting at the ends of nosepiece 121 and ending along cavity closure line 123. Closure of an open cavity typically causes a plume of water to be raised above water surface 130, resulting in a bubbly wake whose loss in energy represents cavity drag. If strut 120 is sufficiently thin, then cavity drag can be much less than the frictional drag of a wetted strut. Below a certain depth, strut drag can be minimized in a lower region 119 by forming cavity 127 that closes along line 126. Typically, the pressure in cavity 127 is less than atmospheric, so fence 124 is needed to separate this cavity 127 from the upper cavity 123. Air for the closed cavity 127 can be introduced through holes 125 from a duct inside the strut, through spanwise slots lying behind nosepiece 121, or through holes 124A in fence 124 shown in Figure 23B. In some cases, the closed cavity pressure can be made atmospheric, so fence 124 is not needed. To separate cavity 127 from a cavity on the upper surface of hydrofoil 129, a bottom region 128 of the strut is shown fully wetted to act as a fence between these cavities.

Figure 24 is a cross section of the upper region of the strut shown in Figures 23A and B. Tail flap 122 is used to control strut side force for turning. The tail flap can either be deflected in the normal steady-state manner out a desired flap angle, or it can be deflected out to a fixed angle and back at a moderate frequency, sometimes called a "bang-bang" control. Optional nose flap 135 can be deflected outward to move cavity 136 outward, if needed, to keep the cavity from wetting the strut under certain operating conditions. Alternatively, outward steps 138 can be placed on the strut sides to deflect cavity 123 away from the strut at lower speeds, or in waves, if needed.

Various nose sections 121, 140 and 142, and ways of attaching the nose sections to struts, are shown in Figures 24-27. Center plate 140 can either be used to support a nosepiece, as in Figures 25 and 27, or it can be the nosepiece itself, as in Figure 26. The upper region of the strut can be ventilated directly from the atmosphere, or additional air can be ejected through the strut to help ventilate the cavity, such as by ejecting air through a permeable member 141.

A ventilated strut can also be swept forward, such as strut 145 in Figure 28, or angled to the vertical, such as strut 146 in Figure 29. Also, a lower portion 148 of strut 120 can be spring loaded by means of spring 147 shown in Figure 30 to permit attached hydrofoil 129 to move vertically relative to the craft in order to reduce craft motion in waves. If the hydrofoil does not provide the necessary damping, a damping device can be added in parallel with the spring means. Alternatively, the entire strut and hydrofoil system can be spring loaded to reduce motion in waves.

The drag of underwater propeller blades or rotors can be reduced by using gas cavities, such as by superventilating 151S the upper, or forward, surface 151A of blade 151, attached to hub 150, as shown in Figure 31. A very efficient, new way to reduce drag on a propeller or rotor blade is to superventilate 152S the lower, or rearward, surface 152B of a blade 152, and form a closed cavity 152C on the upper, or forward, surface 152A, as shown by blade 152 in Figure 32. Another very efficient way to reduce propeller frictional drag is to form closed cavities 153C, 153D on each side 153A, 153B of each blade, such as blade 153 shown in Figure 33.

Instead of driving a propulsor with shafting, an electric motor 155 can be housed in pod 154 shown in Figure 34 that drives a propulsor such as shrouded propeller 156, where shroud 157 is supported by vanes 158. By cambering the shroud outward, such as in a pumpjet, the water pressure inside the shroud can be increased above depth pressure, thus reducing cavitation on the rotor blades.

A problem associated with craft having fully submerged hydrofoils, such as the hydrofoil craft design shown in Figure 1, is that an automatic control system is needed to dynamically stabilize the craft. A bow lifter, such as a surface piercing, inverted, sweptback v-hydrofoil 163, as shown in Figures 35 and 36, can be attached to hull 160 of hydrofoil boat 162 to stabilize the boat in heave, pitch and roll. For example, if boat 162 were lowered in the water, then the lift of bow hydrofoil 163 would increase, the bow would rise, and hydrofoil 3 would also rise due to the increased angle of attack. Similarly, if the boat pitch suddenly increased, then hydrofoil 3 would rise to bring pitch back to normal. Although boat 162 is shown with an outboard drive 161, the same type of bow hydrofoil 163 may be used with a larger boat or ship. In case of a sudden roll, Figure 36 shows that one side of bow hydrofoil 163 would lower, and the other side would rise, causing a hydrodynamic moment that restores the boat angle back to level. A different type of bow lifter is a series of flexible parallel planing plates 164, shown in Figure 37 to stabilize a craft in heave and pitch, and also roll if the span is large enough. Many other kinds of bow lifters can be used, including ski-like lifters that look much like the lifter shown in Figure 37; two side-by-side skis can provide roll stability. The bow lifter could also be shaped like a cut-off bow of a boat placed below the hull bow, such as shown in Figure 2; two such cut-off bows can provide roll stability.

Another way to stabilize a hydrofoil boat in roll is to angle the ends of hydrofoil 3 upward to pierce the water surface, as shown in Figure 38 by a hydrofoil with midsection 165, and lifting end sections 167. In this case, fences 166 are needed to separate adjacent cavities, especially if hydrofoil section 167 is outfitted with different kinds of cavities above fence 166. Since the boat is now stabilized in roll, bow hydrofoil 163 could be replaced by bow hydrofoil 168 shown in Figure 39, which is a surface piercing v-hydrofoil with positive dihedral. Hydrofoil 168 would provide the needed heave and pitch stability.

Also shown in Figure 39, are tip hydrofoils 169 for reducing the induced drag of the hydrofoil. These tip hydrofoils serve to increase the aspect ratio of the main hydrofoil by increasing its span and changing the flow pattern near each end. The tip hydrofoils can be angled up or down relative to the main hydrofoil, and can be either fully wetted or have a closed cavity on one or both surfaces. The tip hydrofoils can also be placed at an angle of attack to the flow in order to generate a vortex that is opposite in direction to the usual tip vortex generated near each end of a main hydrofoil to reduce induced drag.

Another way to stabilize a hydrofoil boat is to retain hydrofoil 3, but support it with aft angled struts 5A designed to provide lift and stabilize the boat in roll. Struts 5A would then become surface piercing hydrofoils.

Still another version of a hydrofoil boat is to reverse hydrofoil 3A so it is swept forward, and angle ends 5B of hydrofoil 3A upward, as shown in Figure 40 to stabilize the boat in heave, pitch and roll. Aft, single strut 4A now supports the vee tip 169 of hydrofoil 3A. Strut 4A could instead be swept down and back.

There are a wide variety of ways to stabilize a hydrofoil boat in heave, pitch and roll, including the addition of bow lifting means, and angling sections of hydrofoil 3 and angling struts, any of which can be wetted, or vented with cavities to reduce drag.

To improve performance on high speed hydrofoil boats or ships, aerodynamic lift can be used to supplement hydrodynamic lift. For example, wing 170 in Figure 41 can be added to augment the lift of hydrofoil 3 to support hull 160 above water. Propeller 174 is shown attached to canted shaft 173 to drive the boat. Alternatively, outboard motors can be used, or an air propulsion system. Vertical air stabilizer 172, and horizontal air stabilizer 171 can provide aerodynamic stability in pitch and yaw. Wing 170, due to its closeness to the water surface, and the resulting ground effect, can provide heave and pitch stability. Alternatively, aerodynamic control surfaces can be used to control heave, pitch and roll. Also, hull 160 can be shaped to augment lift, instead of wing 170, especially if the hull is a catamaran or a trimaran where the cross structure can be shaped to generate lift.

In the various hydrofoil craft designs shown herein, the hull does not have to be supported entirely above water; instead, the hull could remain in contact with the water, in which case hull lift would be augmented by hydrofoil lift.

Air cavities can be used in a wide variety of ways to reduce drag on underwater surfaces. Figs 42 and 43 illustrate a way to use closed air cavities to reduce drag on the sides and bottom of surface ship 180. A discontinuity or step 182 at the end on each side of nosepiece 181 forms a side cavity 183. A series of multiple steps 184 are placed downstream to form additional closed cavities 185 that terminate by wetted tailpiece 186. Frictional drag on the bottom surface 190 is minimized similarly, starting with nose step 187 and closed cavity 187C, followed by multiple steps 187 and cavities 187C, until reaching wetted tailpiece 186. The surface 192 underlying each cavity is curved somewhat like the cavity surface 194, and is designed to minimize the contact angle 196 at the end of each cavity. A fence is needed between each side cavity and each adjacent bottom cavity. The cavity lengths on the bottom are not necessarily the same as the lengths of the side cavities. Also, the height and angle of the various surfaces ahead of each step tend to vary with depth, and with downstream station. Typically, cavities are longer and thinner near the surface than near the bottom. At the very surface, the side cavity shapes tend to be parabolic, so here the cavities tend not to close; however, as depth increases, the side cavities will close. Because of this depth effect, steps 187 tend to increase in height toward the bottom. Since cavity shapes change with speed, step heights can either vary in height with speed, or step heights can be designed for a specific speed, and more steps added for use at lower speeds.

The hull shown in Figure 44 is similar to that in Figure 42, except it is essentially under underwater, so it has an upper surface 198 that is also covered with closed cavities 189, formed by a series of steps 188 to generate a series of cavities 189 to reduce drag. Nose and tail sections, 181 and 186, pierce the surface to provide air for the cavities, and provide heave and pitch stability; roll stability is achieved by placing the center of gravity below the center of buoyancy.

In the many embodiments described herein, each can be used with others, or parts of each can be combined with parts of others, to enhance efficiency or performance. Also, automatic control systems, in conjunction with a variety of sensors, can be used to control any moving part in order to dynamically control craft motion, or to control cavity effectiveness.

While the invention has been described with reference to specific embodiments, modifications and variations of the invention may be constructed without departing from the scope of the invention, which is defined in the following claims.

We claim:

1. A hydrofoil craft comprising at least one hull that lies at least mostly above water, a propulsion system, and at least one strut whose upper end is attached to the at least one hull and whose lower end is attached to a fully-submerged dynamically-lifting hydrofoil, the hydrofoil further comprising a leading edge and a trailing edge, a substantially continuous upper surface and a substantially continuous lower surface, a spanwise discontinuity in each surface near the leading edge for causing a local water boundary layer to separate from each surface, at least one gas source, a gas releaser behind the discontinuity on each surface for forming a cavity that extends rearward along each surface from the discontinuity to a cavity closure region near the trailing edge, a gas flow restrictor connected to each gas releaser for limiting gas released into each cavity and ensuring that each cavity closes ahead of the trailing edge, wherein pressure in the cavity on the upper surface is less than pressure in the cavity on the lower surface, wherein most of the upper and lower surfaces of the hydrofoil lie within the cavities, and wherein each surface in the cavity closure region is shaped for closing the cavity on that side relatively smoothly by minimizing a cavity contact angle between the cavity wall and the surface.

2. The hydrofoil craft of claim 1, further comprising at least one trailing edge flap positioned along at least a portion of the trailing edge.

3. The hydrofoil craft of claim 1, further comprising at least one fore-and-aft fence positioned along the surfaces for separating at least one of the cavities into multiple adjacent cavities positioned on one or both surfaces of the hydrofoil, wherein the at least one fence comprises a solid barrier or a strip of fully wetted flow.

4. The hydrofoil craft of claim 1, further comprising a controller for supplying additional gas to the cavity on the lower surface for permitting the cavity to extend beyond the trailing edge for increasing hydrofoil lift.

5. The hydrofoil craft of claim 1, further comprising a series of parallel ridges placed in the cavity closure region near a desired cavity closure location, wherein the ridges are angled to within 30 degrees of a water flow direction, and wherein cross sections of the ridges comprise a series of essentially symmetrical saw-tooth-like shapes.

6. The craft of claim 1, wherein an above-water portion of the craft provides aerodynamic lift, and makes use of the water proximity for further increasing the aerodynamic lift by using a ground effect.

7. A hydrofoil craft including a structure that lies at least mostly above water, a propulsion system, and at least one strut having an upper end and a lower end, the upper end attached to the structure, and the lower end attached to a fully-submerged dynamically-lifting hydrofoil, the hydrofoil comprising a substantially continuous upper surface, a substantially continuous lower surface, a leading edge, a trailing edge, a spanwise nosepiece that is angled downward or rearward from the leading edge to form a wetted spanwise surface, wherein the upper edge of the nosepiece has an upper discontinuity that forms an upper cavity on the upper surface of the hydrofoil, and the lower edge of the nosepiece has a lower discontinuity that forms a lower cavity on the lower surface of the hydrofoil, wherein the nosepiece surface in cross section is flat, convex or concave, and further comprising at least one gas source, a gas releaser behind each discontinuity for forming the cavities that extend rearward, and a gas flow restrictor communicating with each gas flow releaser for ensuring that each cavity closes

ahead of the trailing edge.

8. A hydrofoil craft comprising at least one hull that lies at least mostly above water, a propulsion system connected to the craft, at least one strut having an upper end and a lower end, the upper end attached to the at least one hull, a fully-submerged dynamically-lifting hydrofoil attached to the lower end, the hydrofoil comprising an essentially continuous upper surface on a top of the hydrofoil, an upper trailing edge at an aft end of the upper surface, an essentially continuous lower surface on a bottom of the hydrofoil, and a lower trailing edge at an aft end of the lower surface, wherein the surfaces have a common leading edge, further comprising a spanwise discontinuity in each surface near the leading edge of the hydrofoil for causing a local water boundary layer to separate from each surface, at least one gas source connected to the craft, a gas releaser on each surface behind the discontinuity for forming upper and lower cavities that extend rearward, a gas flow restrictor for limiting a gas flow into the upper cavity for ensuring that the upper cavity closes ahead of the upper trailing edge on the upper surface, a gas supply connected to the lower surface for ensuring that the lower cavity on lower surface extends beyond the lower trailing edge on the lower surface, wherein pressure in the upper cavity on the upper surface is lower than pressure in the lower cavity on the lower surface, and wherein most of the upper surface of the hydrofoil lies within the upper cavity.

9. A hull comprising an elongated low-drag hull having opposite sides, a propulsion system connected to the hull, a symmetrical and essentially-continuous side surface on each of the opposite sides, a leading edge, a trailing edge, a bottom surface, at least one source of pressurized air, multiple vertically-extending discontinuities lying between the

leading edge and the trailing edge on each side surface for separating a water boundary layer and forming rearward-extending cavities open to the atmosphere, wherein at least a portion of the hull lies above the water surface, and further comprising at least one pressurized thin air cavity formed on the bottom surface for reducing frictional drag.

10. The hull of claim 9, wherein the hull lies essentially under a water surface, further comprising a thin surface-piercing member with an air duct inside connected to the cavities for providing air for the cavities, and additionally comprising an upper hull surface having essentially transverse discontinuities for separating a water boundary layer for forming multiple air cavities on the upper hull surface filled with air at less than depth pressure.

11. Apparatus for reducing drag comprising an essentially continuous underwater surface, at least one spanwise discontinuity on the surface for separating a water boundary layer from the surface, at least one gas source, a gas releaser behind the discontinuity for forming a cavity that extends rearward on the surface from the discontinuity, a desired cavity termination region on the surface behind the discontinuity, a gas flow limiter connected to the gas releaser for limiting gas flow into the cavity for ensuring that the cavity closes in the desired cavity termination region without gas being artificially withdrawn from the cavity, wherein the surface in the desired cavity termination region is shaped for a minimum of a cavity contact angle, wherein at least a portion of the surface that lies behind the desired cavity termination region is shaped for increasing the cavity contact angle to help close the cavity in case the cavity extends beyond the desired termination region.

12. The apparatus of claim 11, wherein the discontinuity is a plate extending outward from the surface a fixed or a controllable distance and angled at an acute angle up to approximately perpendicular to the surface.

13. The method of reducing drag on an essentially continuous underwater surface comprising providing a surface discontinuity on the surface that is angled to water flow along the surface, separating a water boundary layer from the surface, providing at least one gas source, releasing gas behind the discontinuity, forming a cavity, extending the cavity rearward from the discontinuity, limiting gas flow rate into the cavity, ensuring that the cavity closes ahead of a trailing edge of the surface without gas being artificially withdrawn from the cavity, wherein providing the discontinuity comprises providing and angling a plate at an acute angle or at approximately about 90 degrees to the surface, and extending the plate outward from the surface a fixed distance or a controllable distance.

14. The method of closing a gas cavity comprising providing a moving underwater surface, providing gas to the surface, forming a gas cavity on the surface, providing a cross section of the surface transverse to water flow over the surface, providing a desired cavity closure in a cavity closure region, providing a series of substantially symmetrical saw-tooth-like shapes on the surface in a cross section of the cavity closure region.

15. The method for reducing drag on a hydrofoil comprising providing a hydrofoil, providing an essentially continuous upper surface on a top of the hydrofoil, providing an essentially continuous lower surface on a bottom of the hydrofoil, joining the surfaces at a common leading edge and at a common trailing edge, providing a plate extending outward from the surfaces a fixed or controllable distance, and angling the plate at an acute angle, a controllable angle or approximately perpendicular to the surfaces,

extending the plate at least partially in a spanwise direction on at least one of the surfaces near the leading edge, using the plate to separate a water boundary layer from the at least one of the surfaces, providing at least one gas source, releasing gas behind the plate, forming a gas cavity, extending the gas cavity rearward from the plate, limiting gas flow rate into the cavity, closing the cavity ahead of the trailing edge, shaping the at least one of the surfaces in a desired cavity termination region for a minimum cavity contact angle, providing at least a portion f the at least one of the surfaces that lies behind the desired cavity termination region with a shape for increasing the cavity contact angle in case the cavity extends beyond the desired termination region.

16. The method of reducing drag on a hydrofoil comprising providing an essentially continuous upper surface on a top of the hydrofoil, providing an essentially continuous lower surface on a bottom of the hydrofoil, providing the surfaces with a common leading edge and a common trailing edge, providing a spanwise nosepiece that is angled downward or rearward from the leading edge to form a wetted spanwise surface, providing an upper discontinuity along the leading edge that forms an upper cavity on the upper surface of the hydrofoil, providing a lower discontinuity along the lower edge of the nosepiece to form a lower cavity on the lower surface of the hydrofoil, providing shaping the cross section of the nosepiece to be flat, convex or concave, and further providing at least one gas source, releasing gas behind the discontinuity on each surface forming cavities on the surfaces, extending the cavities rearward from the discontinuities, and limiting gas flow rate into at least one cavity to ensure that it closes ahead of the trailing edge.

17. The method of claim 16, further comprising providing the hydrofoil with a v-shaped

planform, and sweeping the leading edge at least 45 degrees fore or aft.

18. The method of supplying gas into a gas cavity on a hydrofoil surface, comprising providing a lifting hydrofoil, providing a gas cavity on the hydrofoil, providing a gas source, flowing gas from the gas source through a spanwise duct in a strut that is attached to a hydrofoil, through at least one opening in the hydrofoil in a strut attachment region into a spanwise duct in the hydrofoil, and through a permeable wall into at least one spanwise opening in the hydrofoil into the cavity.

19. The method of claim 18, wherein the flowing gas through at least one spanwise opening into the cavity comprises flowing the gas from under a flap that covers an opening in the hydrofoil and hinging the flap on an upstream side.

20. A hydrofoil method comprising supplying gas into gas cavities on the upper and lower surfaces of a hydrofoil by flowing the gas from multiple gas sources through multiple spanwise ducts in at least one strut that is attached to the hydrofoil, through multiple openings in the hydrofoil at strut attachment regions into multiple spanwise ducts in the hydrofoil, and through multiple openings in the hydrofoil into the cavities, and limiting gas flow rate into at least one cavity to ensure that it closes ahead of the trailing edge.

21. A hydrofoil craft comprising at least one hull that lies at least mostly above water, a propulsion system, at least one strut having an upper end attached to a hull and having a lower end, a fully-submerged dynamically-lifting hydrofoil attached to the lower end, an essentially continuous upper surface on a top of the hydrofoil and an essentially continuous lower surface on a bottom of the hydrofoil, wherein the surfaces have a common leading edge and a common trailing edge, further comprising a spanwise

discontinuity on at least one of the surfaces near the leading edge for causing a local water boundary layer to separate, at least one gas source, a gas releaser behind the discontinuity for forming a cavity that extends rearward, a gas flow limiter for limiting a gas flow rate into the cavity for ensuring that the cavity closes ahead of the trailing edge, wherein most of the surface of the hydrofoil on the cavity side lies within the cavity, and wherein the hydrofoil craft further comprises a bow lifter positioned near a front of the craft for stabilizing the craft in at least heave or pitch.

22. The craft of claim 21, wherein the bow lifter comprises a set of side-by-side flexible planing plates wherein an angle of attack of each planing plate reduces as its lift increases.

23. A hydrofoil craft comprising at least one hull that lies at least mostly above water, a propulsion system, a dynamically-lifting hydrofoil for helping to lift at least part of a weight of the craft, the lifting hydrofoil comprising an essentially continuous upper surface on a top of the hydrofoil and an essentially continuous lower surface on a bottom of the hydrofoil, wherein the surfaces have a common leading edge further comprising a spanwise discontinuity on at least a portion of at least one surface near the leading edge for causing a local water boundary layer to separate, at least one gas source, a gas releaser behind the discontinuity for forming a cavity that extends rearward, a gas flow limiter for limiting a gas flow rate into the cavity for ensuring that the cavity closes ahead of the trailing edge, an angled upward tip region at each end of the lifting hydrofoil for piercing a water surface, wherein at least a portion of each tip region near the water surface is lifting for assisting in dynamically stabilizing craft roll, depth or pitch.

24. The craft of claim 23, further comprising a hydrodynamic lifter at a bow of the craft

for dynamically stabilizing the craft in depth.

25. A hydrofoil craft comprising at least one hull that lies at least mostly above water, a propulsion system, a dynamically-lifting hydrofoil for helping to lift part of the weight of the craft, the hydrofoil comprising an essentially continuous upper surface on a top of the hydrofoil and an essentially continuous lower surface on a bottom of the hydrofoil, wherein the surfaces have a common leading edge and a common trailing edge, a spanwise discontinuity on at least a portion of at least one of the surfaces near the leading edge for causing a local water boundary layer to separate, at least one gas source, a gas releaser behind the discontinuity for forming a cavity that extends rearward, a gas flow limiter connected to the gas releaser for limiting a gas flow rate into the cavity for ensuring that the cavity closes ahead of the trailing edge, wherein an above-water portion of the craft provides aerodynamic lift and makes use of water proximity for further increasing the aerodynamic lift by using a surface effect.

26. The hydrofoil craft of claim 1, including a gas flow rate controller, and wherein the at least one gas source, gas releasers and gas flow restrictors are modified to increase the gas flow rate into at least one cavity to extend that cavity beyond the trailing edge in order to control hydrofoil lift.

27. The apparatus of claim 11, including a gas flow rate controller, and wherein the gas flow limiter is modified to increase the gas flow rate into the cavity to intermittently extend the cavity beyond the trailing edge, and wherein the controller controls the gas flow rate into the cavity to control the fraction of time that the cavity extends beyond the trailing edge in order to control the force acting on the surface, and further including one or more fences approximately aligned with the water flow to separate the cavity from

an adjacent cavity.

28. The method of claim 15, and occasionally increasing the gas flow rate into the cavity on the at least one of the surfaces to extend that cavity beyond the trailing edge, or intermittently controlling the gas flow rate into that cavity to control the fraction of time that the cavity extends beyond the trailing edge in order to control hydrofoil lift.

29. The method of claim 28, including forming a gas cavity on the other side of the hydrofoil, and occasionally controlling that cavity similar to the first cavity.

30. The method of claim 28, where the hydrofoil is a fin, strut, or blade of a propeller or propulsor.

31. The method of reducing drag on an essentially continuous underwater surface comprising providing at least one surface discontinuity on the surface, separating a water boundary layer from the surface, providing at least one gas source, releasing gas behind the at least one discontinuity, forming at least one cavity, extending the at least one cavity rearward from the discontinuity, limiting gas flow rate into the cavity, ensuring that the cavity closes in a desired cavity closure region without gas being artificially withdrawn from the cavity, wherein providing the discontinuity comprises providing a curved or flat plate that is angled either way up to about 90 degrees to the surface, wherein the plate extends outward a fixed or a variable distance from the surface.

32. The hydrofoil craft of claim 23, further comprising a strut that connects each hydrofoil or tip region to the craft on each side, wherein the strut is angled upward and inward from the hydrofoil or tip region.

FIG. 1

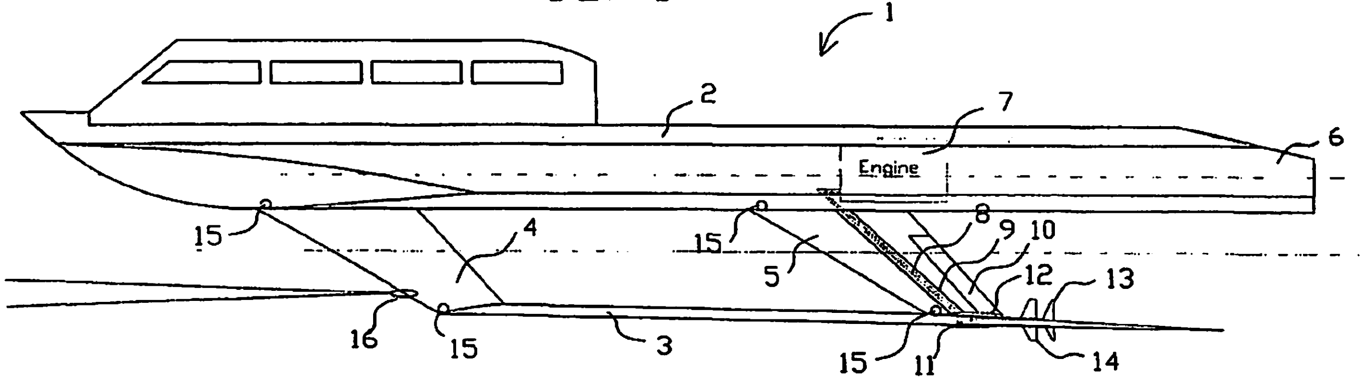

1
2
7
Engine
6
15
4
15
5
8
9
10
12
13
16
15
3
15
11
14

FIG. 2

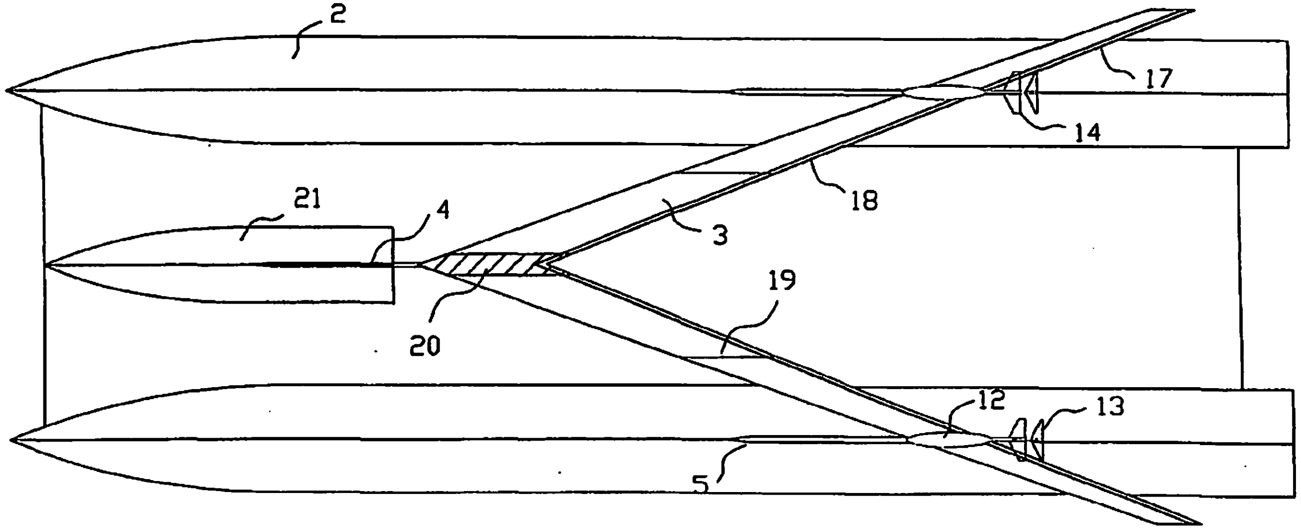

2
17
14
21
4
18
3
20
19
12
13
5

FIG. 3

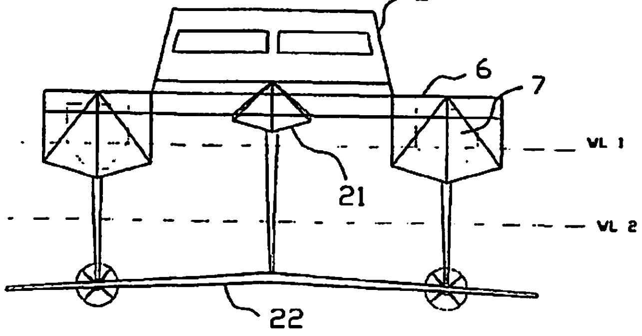


FIG. 4

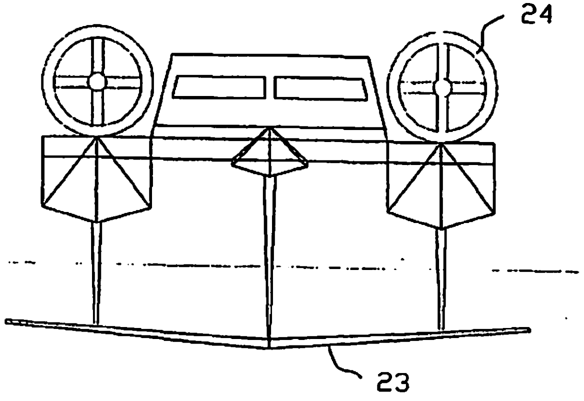


FIG. 5

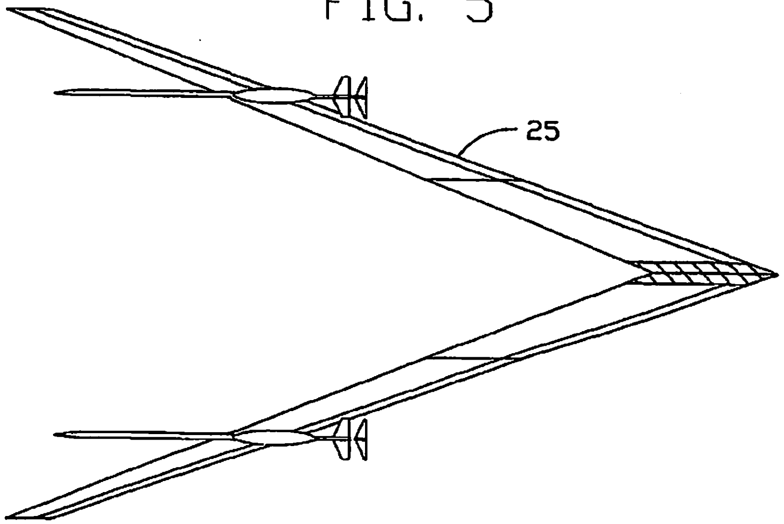


FIG. 6

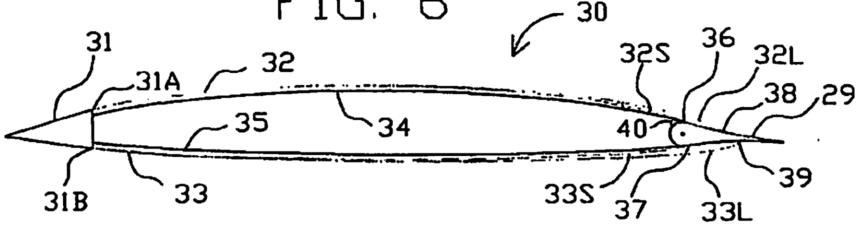


FIG. 8

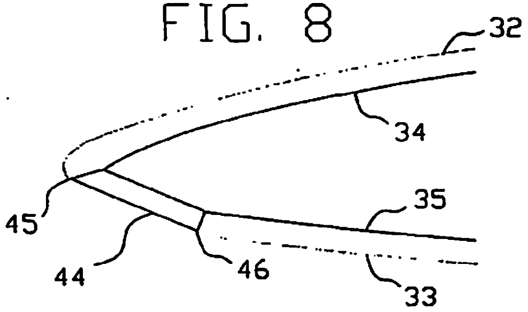


FIG. 7

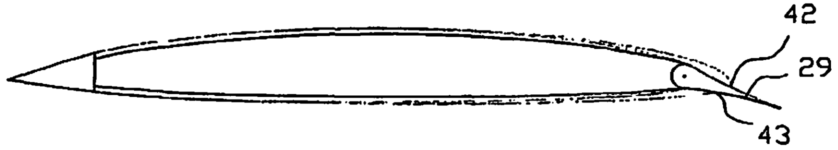


FIG. 9

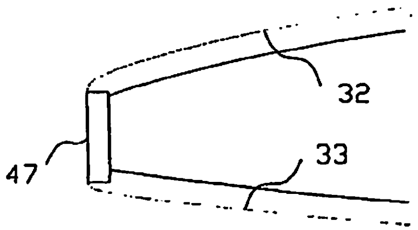


FIG. 10

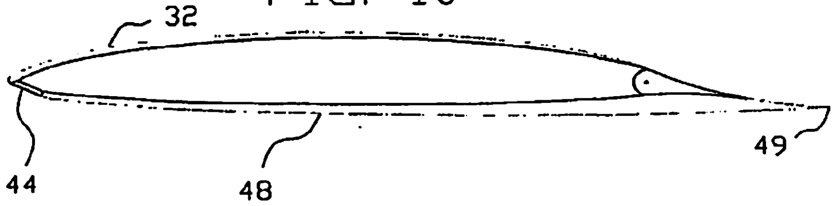


FIG. 10B

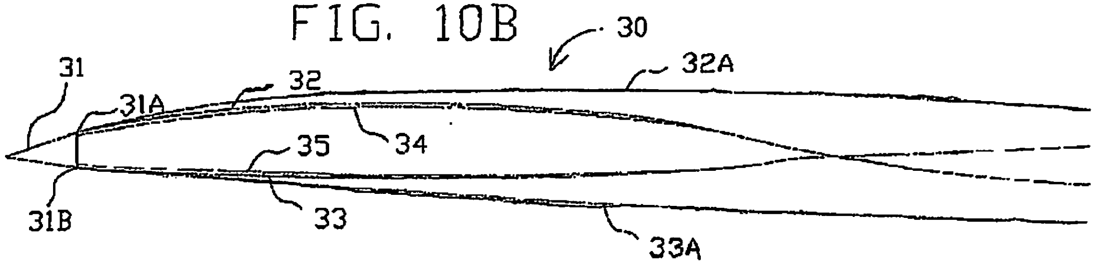


FIG. 11

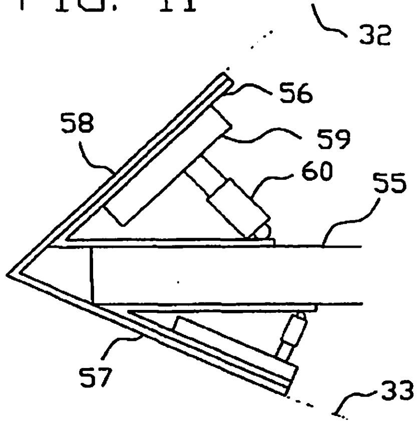


FIG. 12

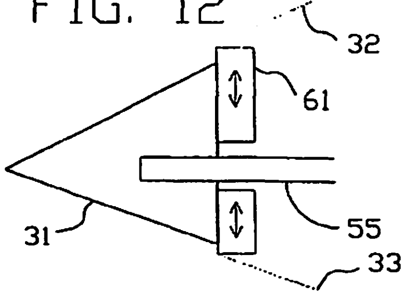


FIG. 13

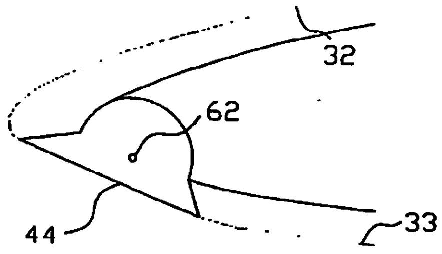


FIG. 15

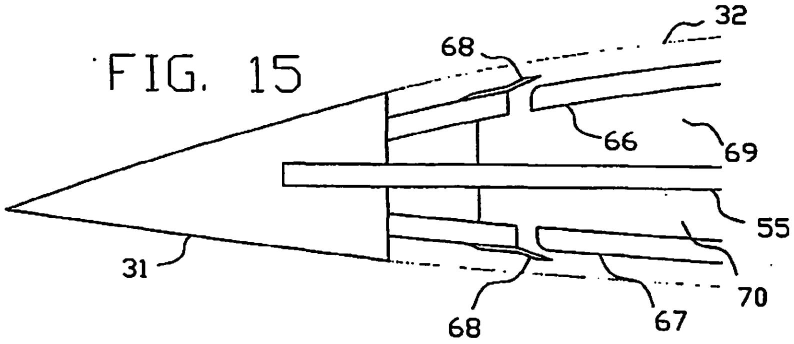


FIG. 14

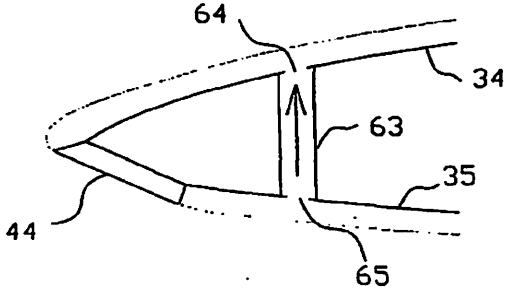


FIG. 16

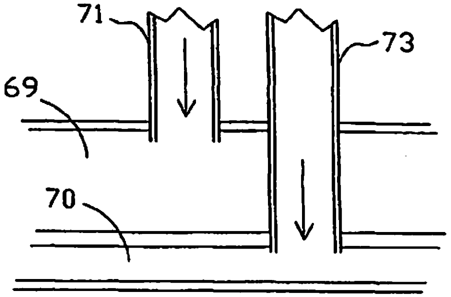


FIG. 17

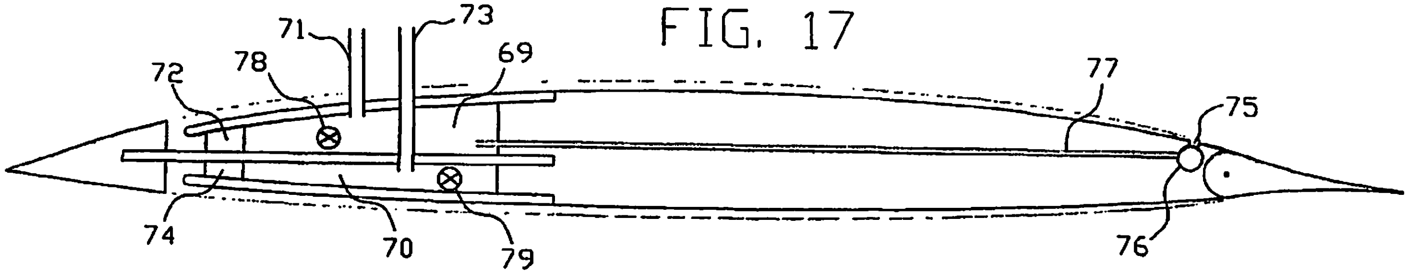


FIG. 18

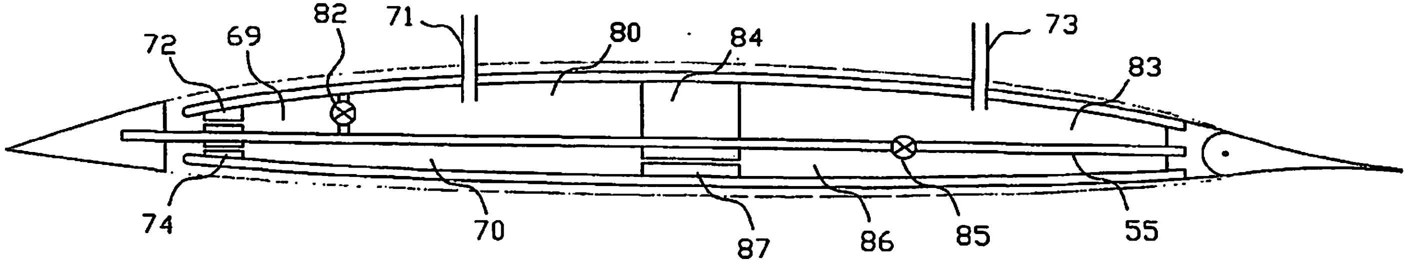


FIG. 19

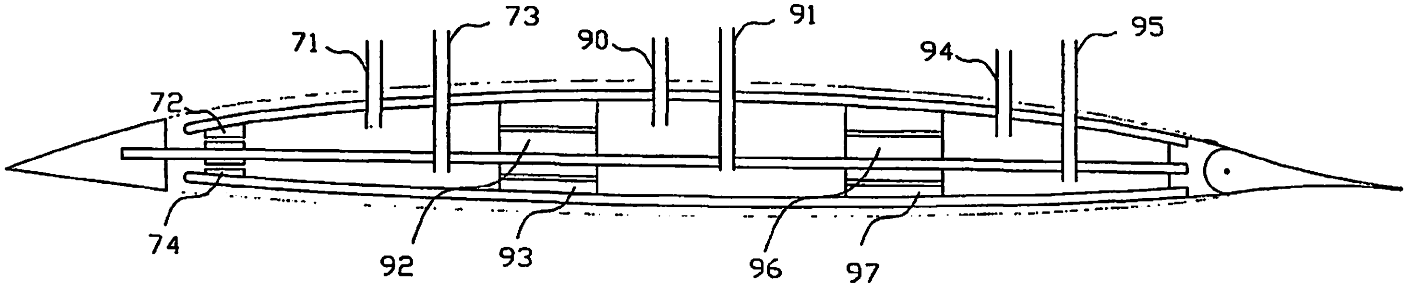


FIG. 20

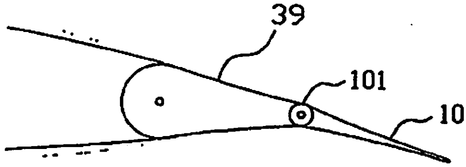


FIG. 21A

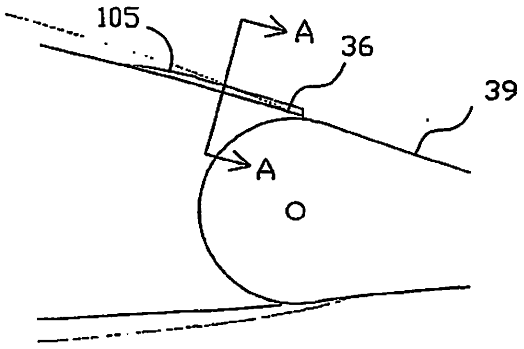


FIG. 21B

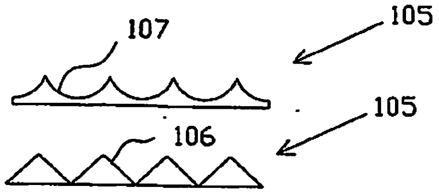


FIG. 22

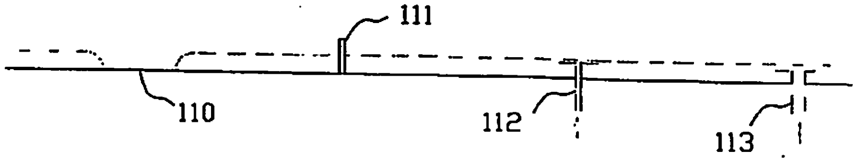


FIG. 23A

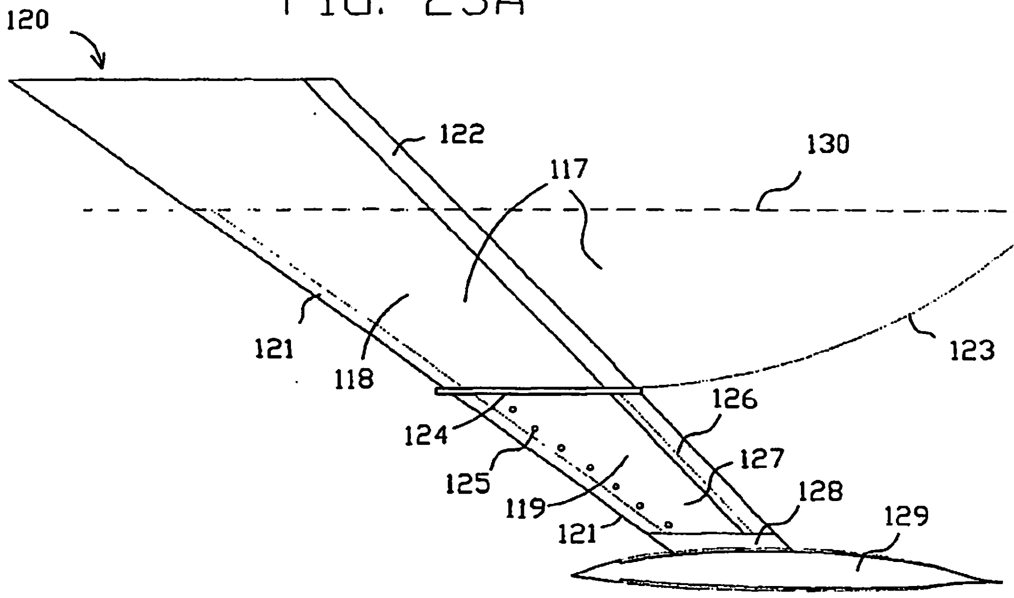


FIG. 23B

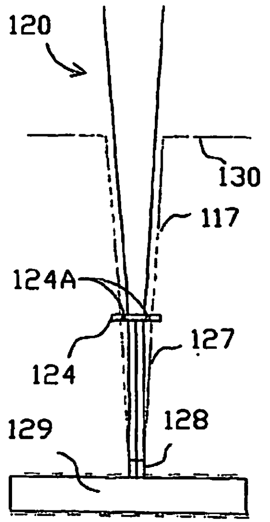


FIG. 24

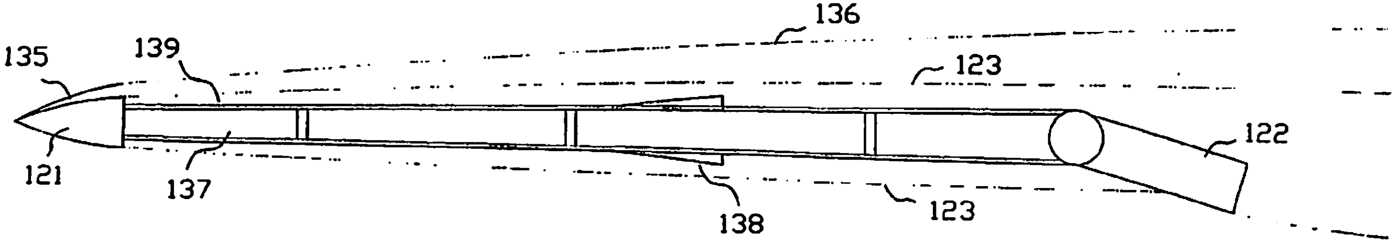


FIG. 25

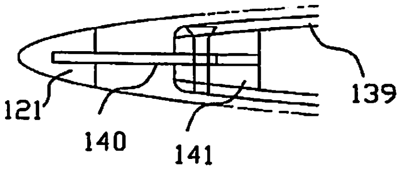


FIG. 26

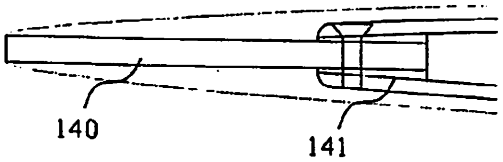


FIG. 27

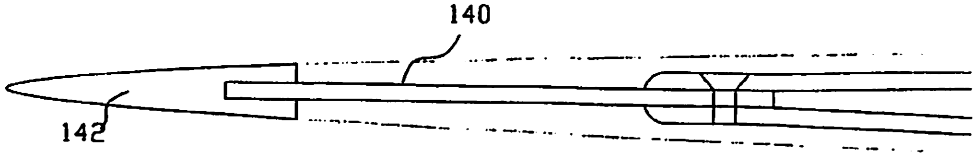


FIG. 28

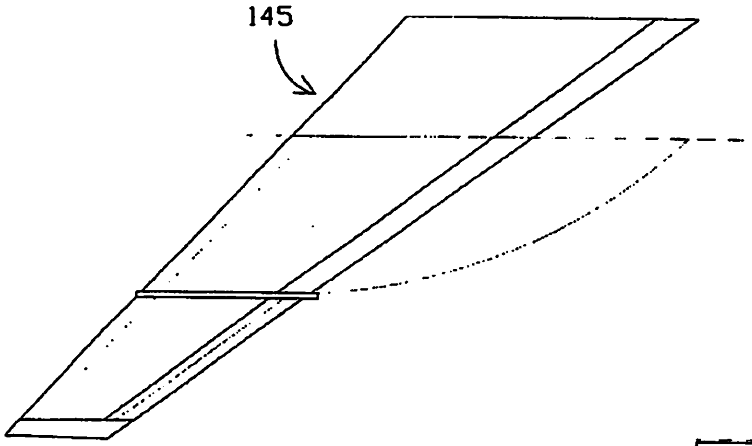


FIG. 29

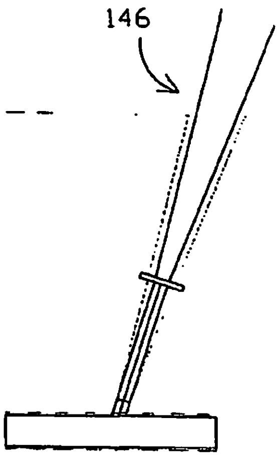


FIG. 30

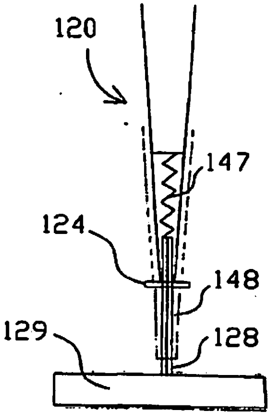


FIG. 31

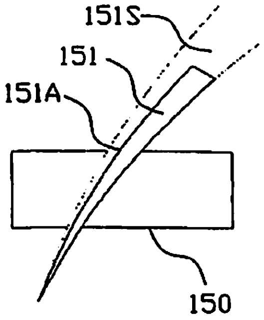


FIG. 32

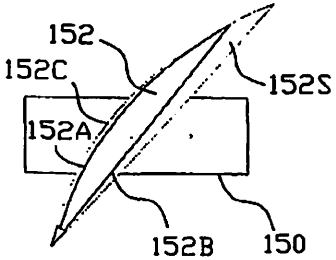


FIG. 33

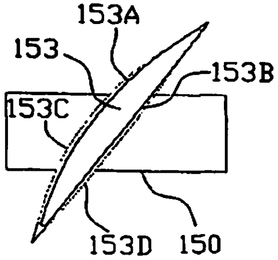


FIG. 34

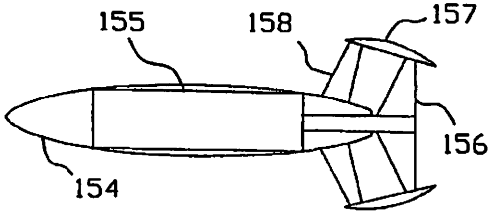


FIG. 35

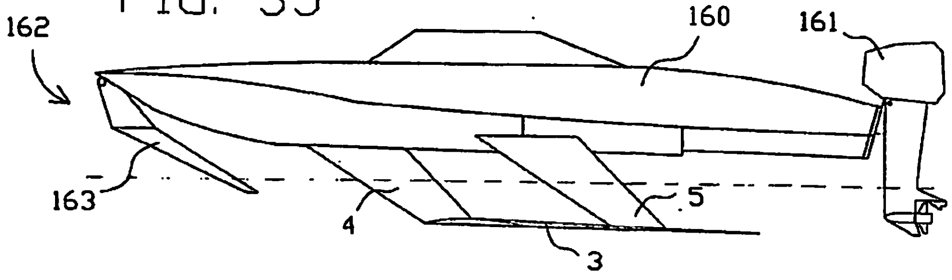


FIG. 36

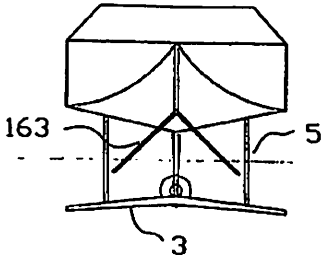


FIG. 37

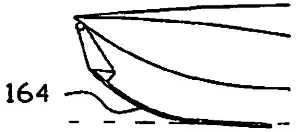


FIG. 38

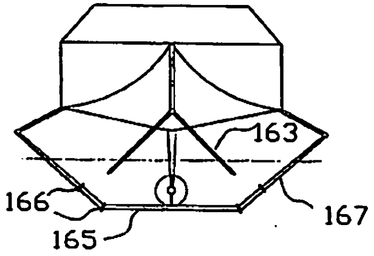


FIG. 39

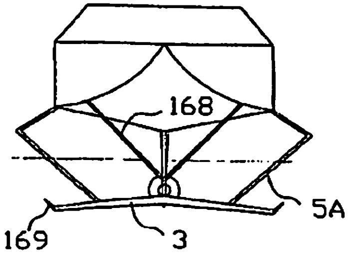


FIG. 40

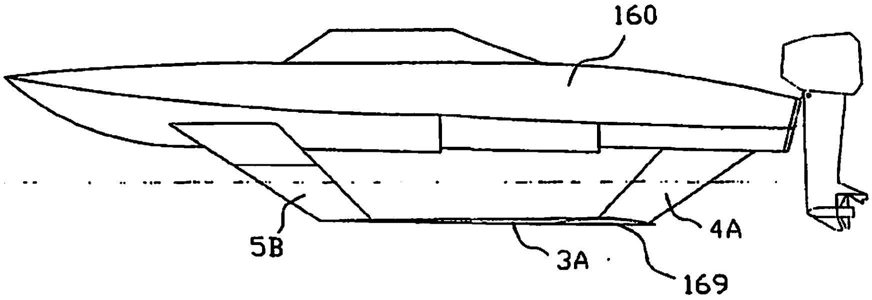


FIG. 41

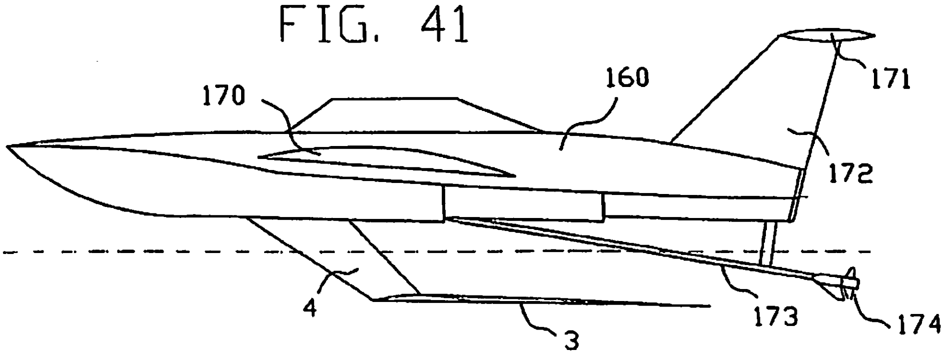


FIG. 42

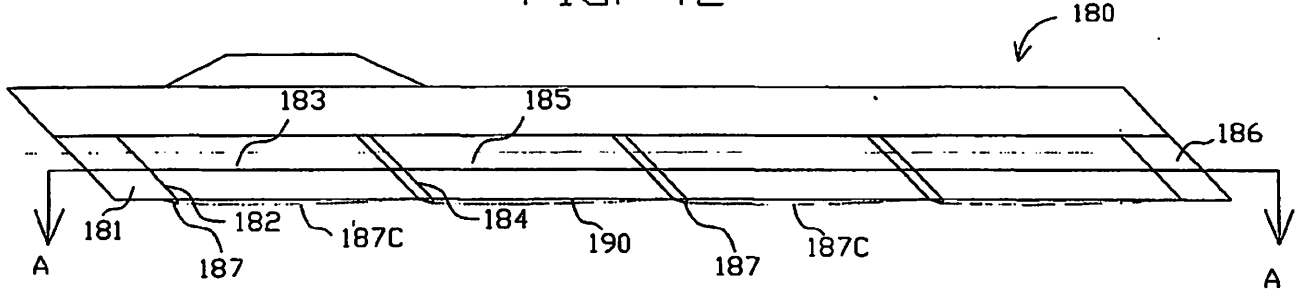


FIG. 43

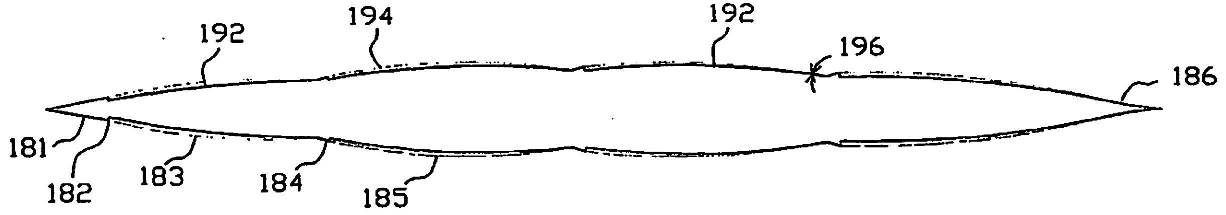


FIG. 44