Oct. 29, 1968 D. Z. BAILEY 3,407,770

HYDROFOIL

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FIG. 1

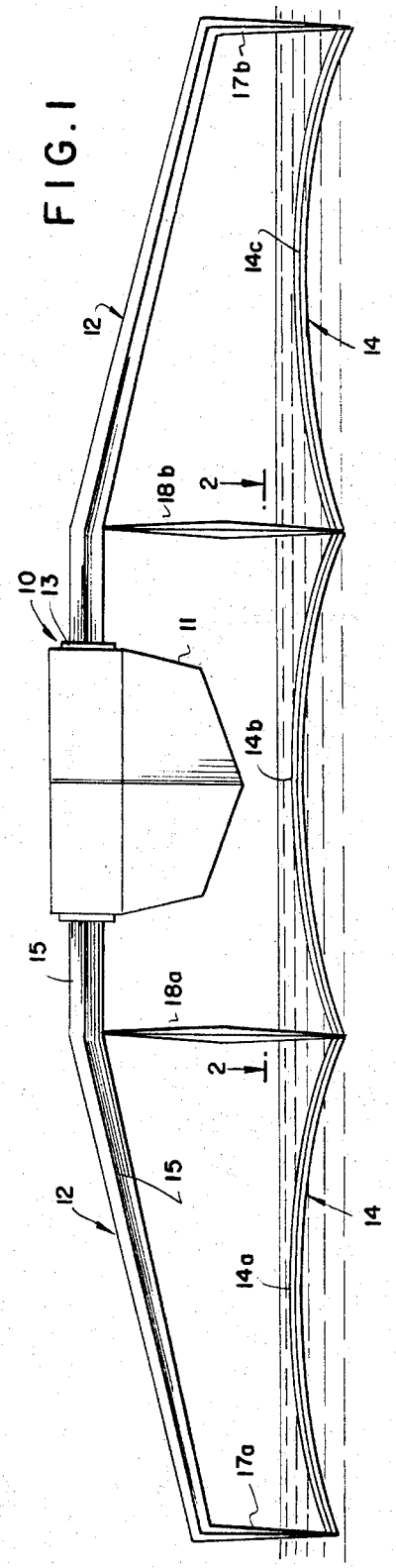


FIG. 2

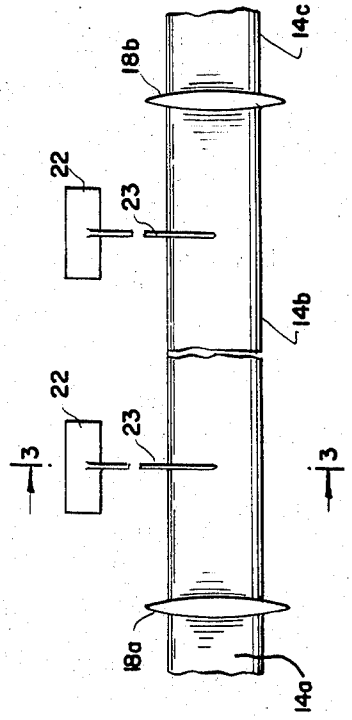
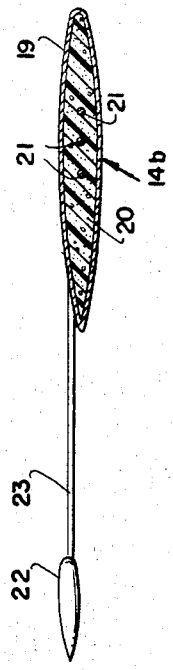


FIG. 3



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FIG. 7

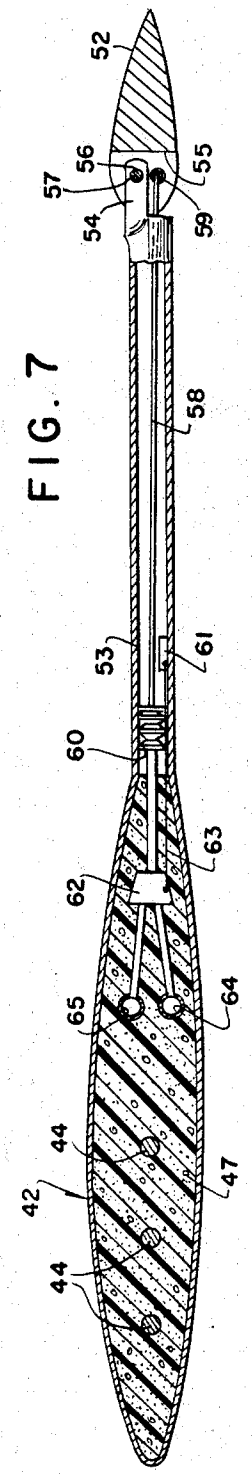


FIG. 4

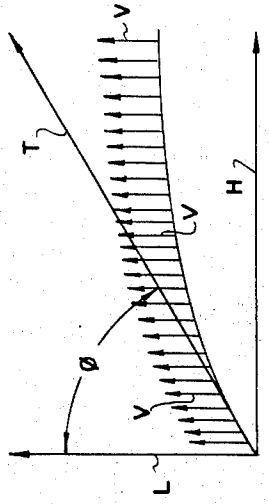


FIG. 5

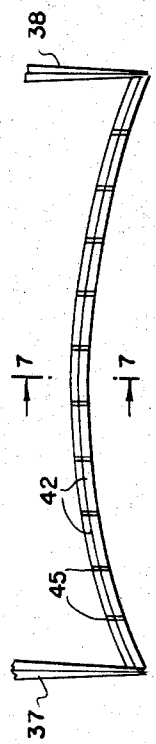
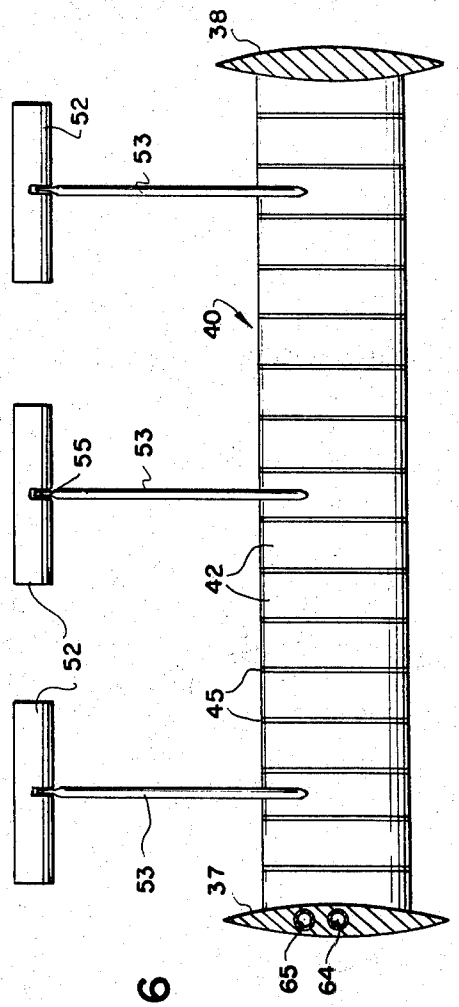


FIG. 6



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HYDROFOIL

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Filed Dec. 2, 1966, Ser. No. 598,643
6 Claims. (Cl. 114—66.5)

ABSTRACT OF THE DISCLOSURE

A submerged-hydrofoil watercraft having an upwardly bowed foil shaped such that substantially only tensile forces are applied in the spanwise direction of the foil, thereby enabling a high aspect ratio to be achieved reducing the drag to lift ratio.

This invention relates to hydrofoil watercraft of the totally submerged foil type and in particular provides a submerged foil structure enabling substantially greater aspect ratios than have heretofore been feasible with submerged foil craft.

The dynamic efficiency of a propelled body in a fluid medium generally is determined by the aspect ratio, e.g., the ratio of the span (wing tip to wing tip dimension) to the chord length (forward edge to trailing edge dimension) of the forwardly moving body. To obtain a high aspect ratio and the high dynamic efficiency associated therewith, it has been proposed that the span of the submerged hydrofoil be extended to its maximum permissible limits by the utilization of additional support struts and thicker hydrofoils to absorb the increased bending moments exerted upon the elongated hydrofoil by the lifting force of the water during running operation. While thicker hydrofoils permit elongated spans and high aspect ratios, they also increase the drag to lift ratio of the hydrofoil in the fluid medium to reduce the dynamic efficiency below optimum. A hyrofoil thickness intermediate the conflicting dimensions necessary for minimum drag and high aspect ratio generally must be accepted as a compromise for design purposes.

It is a primary object of the present invention to provide a submerged hydrofoil construction for hydrofoil craft employing totally submerged foils in which bending moments lengthwise of the span are eliminated, and hence more efficient hydrodynamic design can be employed to reduce the drag to lift ratio and at the same time greater lengths of span can be employed to increase the aspect ratio of the foil.

This and other objects of the invention which will become apparent hereinafter are essentially achieved through the use of a submerged foil positioned between a pair of supports attached to the craft. In accordance with the present invention, the length of the submerged foil between such pair of supports is greater than the lateral spacing between the supports, and the foil assumes, at least under flying conditions, a shape such that the stresses imposed on the foil by the lift exerted on the foil are colinear with the hydrodynamic centerline of the foil, and hence any substantial bending moment cannot exist along the length of the span of the foil. Chordal bending moments will continue to exist, but these moments have no effect on the length of permissible span. It will be apparent that if all the forces of lift exerted along the foil are uniform and normal to the hydrodynamic centerline, the foil will have at least under flying conditions a particircular hydrodynamic centerline. On the other hand, if the foil is designed such that along its length uniform lifting forces are vertical it will be apparent that the hydrodynamic centerline of the foil will have the shape of a catenary curve. In practical construction it is apparent that the height of the center of the foil above its

supported ends is limited by the permissible depth at the supported ends and the necessary submergence of the higher center position of the foil. Under these conditions, very little difference exists between the shape of an arc of a circle and the shape of a catenary curve. Since more efficient lift is achieved by having all lifting forces on the foil acting in a vertical manner uniformly along the span, the description hereinafter will generally have reference to the foil as having a catenary shape.

In general there are two distinct mechanisms in which submerged hydrofoils of the present invention can be constructed. The foil thus can be formed with a permanent shape, such that the hydrodynamic centerline approximates a catenary or other desired curve, even at rest. On the other hand, the foil can be formed as a plurality of discrete, articulated sections along the span of the foil, in which case the foil only assumes the catenary or other shape during flight. In the latter case, the foil has the advantage of permitting flexing of the foil along its length during flight to accommodate local vertical water movement and thus integrates the lifting forces along the length of the entire span, while at the same time preventing the development of any bending moments along the length of the span caused by such local vertical movement of water. It will be noted that small bending moments temporarily are exerted in the first case described above (in which the foil is pre-formed to the desired shape) when local vertical movement of water is encountered.

In another aspect of this invention, whether the foil is pre-formed or articulated, it is contemplated that along the length of the foil short period control systems will be employed in the manner of Patent No. 2,773,467 for correcting the angle of attack of the foil at discrete intervals along its length. In a practical manner such short period of controls would have the form of small foils or vanes rigidly secured to the foil either immediately before the leading edge or, preferably, after the trailing edge of the foil, such that local vertical water movement is sensed and the angle of attack of the immediate section of the foil to which the vane is attached is corrected.

While the attack angle of the submerged foil of this invention can be controlled by a mechanism, such as that disclosed in copending application Ser. No. 546,243, filed Apr. 29, 1966, now U.S. Patent No. 3,345,968, in another aspect of this invention the attack angle can be controlled by controlling the attack angle of the same foils or vanes used to sense local water movement.

For a more complete understanding of the practical application of this invention, reference is made to the appended drawings in which:

FIG. 1 is a front elevation of a watercraft supported by a submerged hydrofoil in accordance with this invention;

FIG. 2 is a section taken along line 2—2 of FIG. 1;

FIG. 3 is a section taken along line 3—3 of FIG. 2;

FIG. 4 is a vector diagram showing the distribution of forces along the hydrofoil in the case in which all lifting forces are vertical and uniformly distributed along the length of the span;

FIG. 5 is a front view of an articulated hydrofoil in accordance with this invention;

FIG. 6 is a top view of the hydrofoil in FIG. 5; and

FIG. 7 is a section taken along line 7—7 of FIG. 5.

Referring more particularly to FIG. 1, there is illustrated in front view a hydrofoil watercraft **10** having a hull **11** attached to which is a hydrofoil structure **12** which is essentially symmetric with reference to a vertical plane on the fore and aft centerline of hull **11**. Foil structure **12** includes a mounting mechanism **13** for changing the angle attack of a submerged foil **14** associated with structure **12** of the type described in copending application 546,243, filed Apr. 29, 1966, which permits foil **14** to be pivotally

moved about a transverse axis approximating its hydrodynamic centerline by movement of mechanism **13** with respect to hull **11**, as described in the above noted copending application. Structure **12** also includes supporting superstructure **15** fixedly attached to mechanism **13** which extends transversely of hull **11** to positions quite remote from hull **11** on each side thereof. The ends of supporting structure **15** carry the depending struts **17***a* and **17***b*, strut **17***a* being the starboard strut and **17***b* being the port strut, while just outboard of hull **11**, structure **15** carries a pair of struts **18***a* on the starboard of hull **11** and **18***b* on the port. Struts **17***a*, **17***b*, **18***a* and **18***b* are preferably shaped to provide a desirable thin hydrodynamic section. Because of the bending moments of the design, struts **17***a* and **17***b* have their thickest sections at their upper ends while struts **18***a* and **18***b* have their thickest sections intermediate their ends.

Referring also to FIGS. 2 and 3, hydrofoil **14** is in three sections, **14***a*, **14***b* and **14***c*, spaced respectively between struts **17***a* and **18***a*, **18***a* and **18***b*, and **18***b* and **17***b*. Each section **14***a*, **14***b* and **14***c* is a solid, unitary structure having a metallic outer skin **19** filled with foamed polystyrene **20** and is of a length greater than a lateral spacing between particular struts **17***a*, **18***a*, **18***b* and **17***b* between which it is positioned and to the lower ends of which its ends are fixedly secured. Internally skin **19** is secured to a plurality of rods **21** which extend lengthwise of each foil **14***a*, **14***b* and **14***c* and are also secured at their ends to the appropriate struts **17***a*, **18***a*, **18***b* and **17***b*. Rods **21** are distributed in a manner equally to absorb spanwise stresses imposed on each foil section **14***a*, **14***b* and **14***c*. The chordal section of foil **14** is changed along its length in a manner that the lifting forces during flight are uniformly distributed vertically along foil **14** and the hydrodynamic centerline of each foil section **14***a*, **14***b* and **14***c* therefore has a catenary shape.

As the chordal section of foil **14** is extremely thin to maximize hydrodynamic efficiency, since it is not required to absorb substantial bending moments, in order to prevent fluctuations in angle of attack of foil **14** along its length caused by localized vertical water movements, a series of flat vanes **22** are attached at equal distances along the span of foil **14** by means of rigid rods **23** which are secured to foil **14** and position vanes **22** in the vicinity of the streamline path of foil **14** aft of its trailing edge but out of its wash. Vanes **22** are positioned also so that they are horizontal and are not only positioned at equal intervals along the span of foil **14**, but have equal areas as well.

As can be seen in the vector diagram of FIG. 4, which represents a half of a section of foil **14**, for example, the outer half of section **14***a*, the lifting pressure produced by the water in response to the forward motion of watercraft **10**, generally represented by vertical vector forces L, is distributed equally along the length of hydrofoil **14***a* as indicated by vectors V. Because hydrofoil section **14***a* is catenary shaped and incapable of developing an appreciable amount of bending moments produced by the lifting vectors V, the major portion of the upward lift L is transmitted by the hydrofoil as a tensile load T to vertical strut **17** with which the tensile load forms an angle ϕ. Tensile load T is composed of vertical force L which equals $T \cos \phi$ and equals one quarter of the portion of the weight of watercraft **10** imposed on structure **12** (assuming sections **14***a*, **14***b* and **14***c* are identical and struts **17***a*, **18***a*, **18***b* and **17***b* are equally spaced and symmetric with respect to the forward and aft center of hull **11**), and a horizontal side load H upon strut **17***a* which equals $T \sin \phi$.

Because hydrofoil sections with a catenary configuration produce greater drafts than a horizontal hydrofoil for a given running submergence, in practical application it is desirable to adjust the geometrical configuration of hydrofoil sections **14***a*, **14***b* and **14***c* such that the angle ϕ is relatively large. The sideloads H thus produced upon struts **17***a* and **17***b* are increased with the sine of the increasing angle ϕ necessitating additional bulk for both structure **12** and struts **17***a* and **17***b* to absorb the increased sideloads. Intermediate struts **18***a* and **18***b* which only need absorb vertical loads, as each catenary foil section is identical, while the side loading on the end struts **17***a* and **17***b* is only that of the half-catenary section it supports.

Referring more particularly to FIGS. 5–7, a hydrofoil section **40** is shown positioned between and fixedly attached at its ends to the lower ends of a pair of vertical struts **37** and **38**. Foil **40** can be used in place of a foil **14**, in which case struts **37** and **38** would correspond to struts **17***a* and **17***b*, respectively. Foil **40** is composed of a plurality of foil sections **42** secured in position relative to one another by tensile bearing steel cables **44** passing transversely through the hydrodynamic cross sectional areas of each of sections **42**. Each adjacent pair of sections **42** is separated by a cushioning layer of compressed neoprene rubber **45** to provide a uniform surface for interaction with the water while permitting hydrofoil **40** to assume a geometrical configuration approximating a catenary in response to the upward forces imposed upon hydrofoil **40** by the forward motion of watercraft **10** relative to the water. Alternatively foil sections **42** can be dove tailed without intermediate layers **45** which can be omitted, particularly when sections **42** have very small span lengths.

Each of hydrofoil sections **42** is packed with foamed polystyrene filling **47** which serves to position tensile bearing cables **44** within the sections while limiting the effect of water seepage upon the buoyancy of the craft. Cables **44** generally are located either at the hydrodynamic pressure centerline **48** or are displaced symmetrically thereabout to equalize the tensile forces carried by each of the cables. The greater flexibility associated with the articulated design of hydrofoil **40** necessitates the utilization of stabilizing hydrofoil vanes, such as vanes **22** which are optional in the case of foil **14**, dependent on its thickness and aspect ratio. Hence, a number of stabilizing vanes **52** are connected to hydrofoil **40** by rods **53** as disclosed in FIG. 7. It is to be realized that the number of stabilizing hydrofoils as well as the shape of the cantenary or other arc formed by the hydrofoil will vary with particular design requirements.

As shown in FIG. 7, each vane **52** is constructed to permit variation in its attack angle with respect to that of the foil section **42** to which it is attached. Thus vanes **52** can serve, not only to stabilize foil **40**, but change its attitude in a long period control system.

Control of attitude of vane **52** is permitted by forming rod **53** as a hollow tube having a vertical flat **54** affixed at its tail end, by slotting the center of the leading edge of vane **52** as indicated at **55** to receive flat **54** and by providing a central pivot pin **56** affixed horizontally in vane **52** which is rotatably received in the appropriately central opening **57** in flat **54**. A control rod **58** which extends lengthwise in tubular rod **53** is pivotally secured at one end to vane **52** adjacent flat **54**, as indicated at **59** approximately beneath pivot pin **56**, and a hydraulic control system is provided within the section **42** to which tubular rod **53** is attached to permit reciprocating movement of rod **58** in rod **53**, thereby to cause vane **52** to rotate about pivot pin **56**. The hydraulic control system typically includes a bellows **60** attached to the forward end of rod **58**, a position sensing device **61** to sense the location of rod **58**, hydraulic amplifier **62** controlled in part by position sensing device **61** as indicated by line **63** and controlled in accordance with a reference system located on the craft to which foil **40** is attached. A tube **64** is provided which extends lengthwise through foil **40** in the same manner as cables **44**, except that it is extended up one of struts **37** and **38** to a master hydraulic system to supply hydraulic fluid for supplying bellows **60** through amplifier **62**. Thus, when a change in the attitude of vane **52** is desired, the operator of the watercraft sends a control signal to amplifier **62** which is referenced against the position of rod **58** detected by detector **61** by means of an error

detector in a conventional manner to operate amplifier **62** to admit fluid to bellows **60** from tube **64** or to exhaust fluid from bellows **60** into an exhaust return line **65** which is extended through foil **40** in the same manner as tube **64** and up to the watercraft through one of struts **37** and **38**.

What is claimed is:

1. A hydrofoil structure for applying lifting force to a watercraft by the forward dynamic motion of said hydrofoil structure relative to said water comprising, a pair of support members attached to said craft transversely separated from each other, a hydrofoil of hydrodynamic cross-sectional area attached at the ends thereof to said supports and having a span intermediate said supports greater than the lateral spacing of said supports, said hydrofoil having a high ratio of length to the least radius of gyration and an upwardly bowed, arcuate shape during flying operation of said watercraft such that lifting forces applied to said foil produces substantially only tensile forces in the spanwise direction of the foil.

2. A hydrofoil support according to claim **1** wherein said hydrofoil is a solid, unitary structure.

3. A hydrofoil support according to claim **1** wherein said hydrofoil is composed of a plurality of articulated, hydrodynamically shaped sections.

4. A hydrofoil support according to claim **3** wherein tensile bearing cables are passed transversely through the hydrodynamically shaped sections.

5. A hydrofoil structure according to claim **1** which further includes a vane attached to the trailing edge of said hydrofoil and positioned in the path of said hydrofoil whereby said foil senses local vertical water movements and flexes said foil where attached thereto to correct the attack angle of said foil to correct for the change therein caused by such local vertical water movement.

6. A hydrofoil structure according to claim **5** in which the attitude of said vane is controllable independently of the attitude of said hydrofoil.

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