Oct. 10, 1967 D. Z. BAILEY 3,345,968

HYDROFOIL

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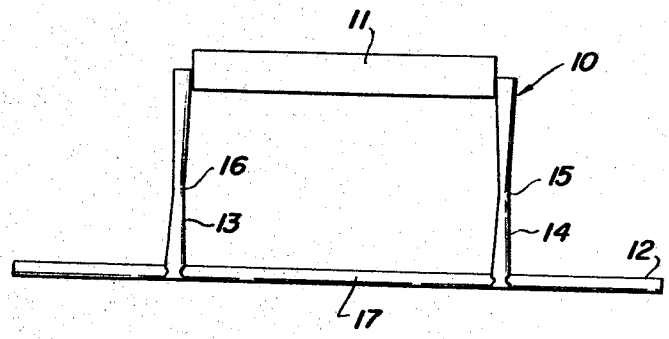


FIG. 1

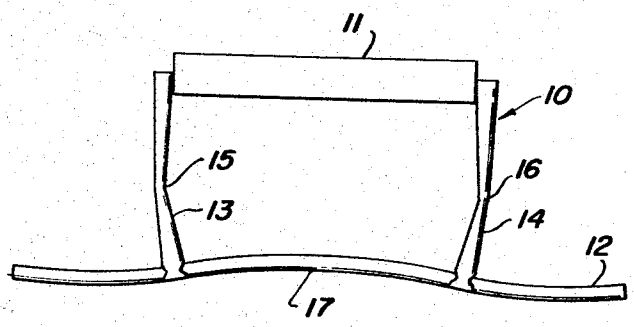
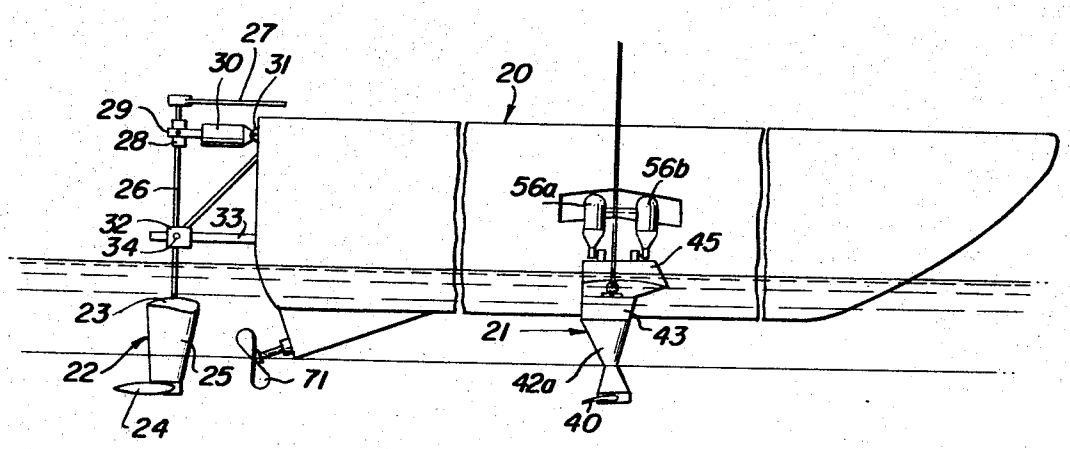


FIG. 2

FIG. 3



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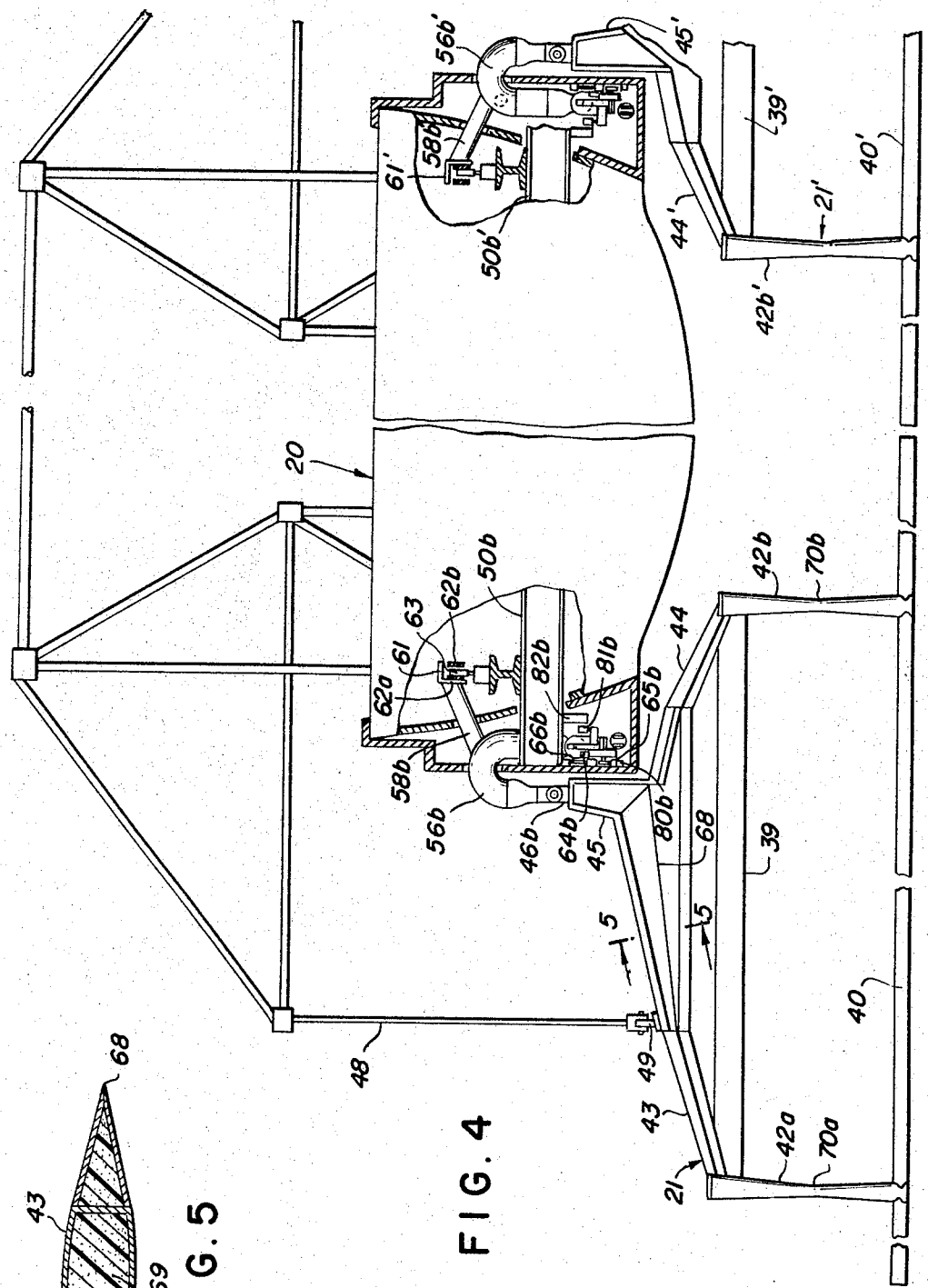


FIG. 4

FIG. 5

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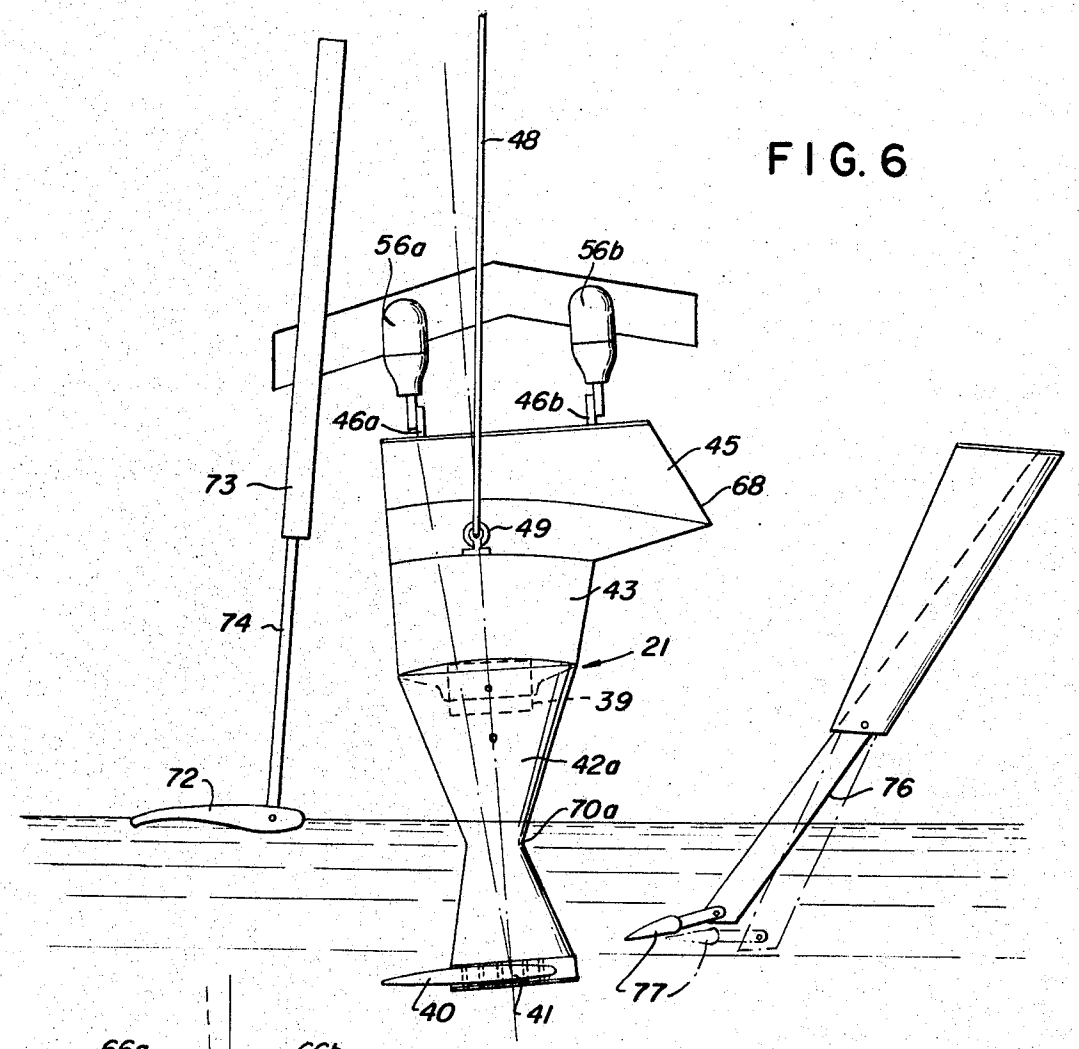
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HYDROFOIL

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FIG. 6



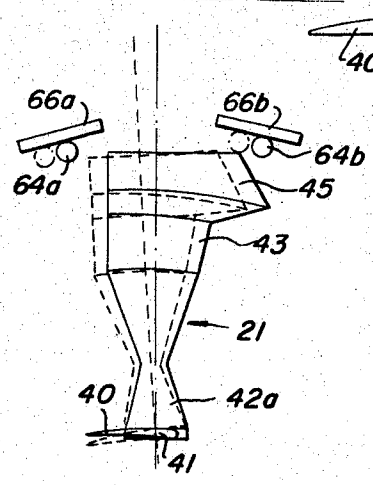


FIG. 9

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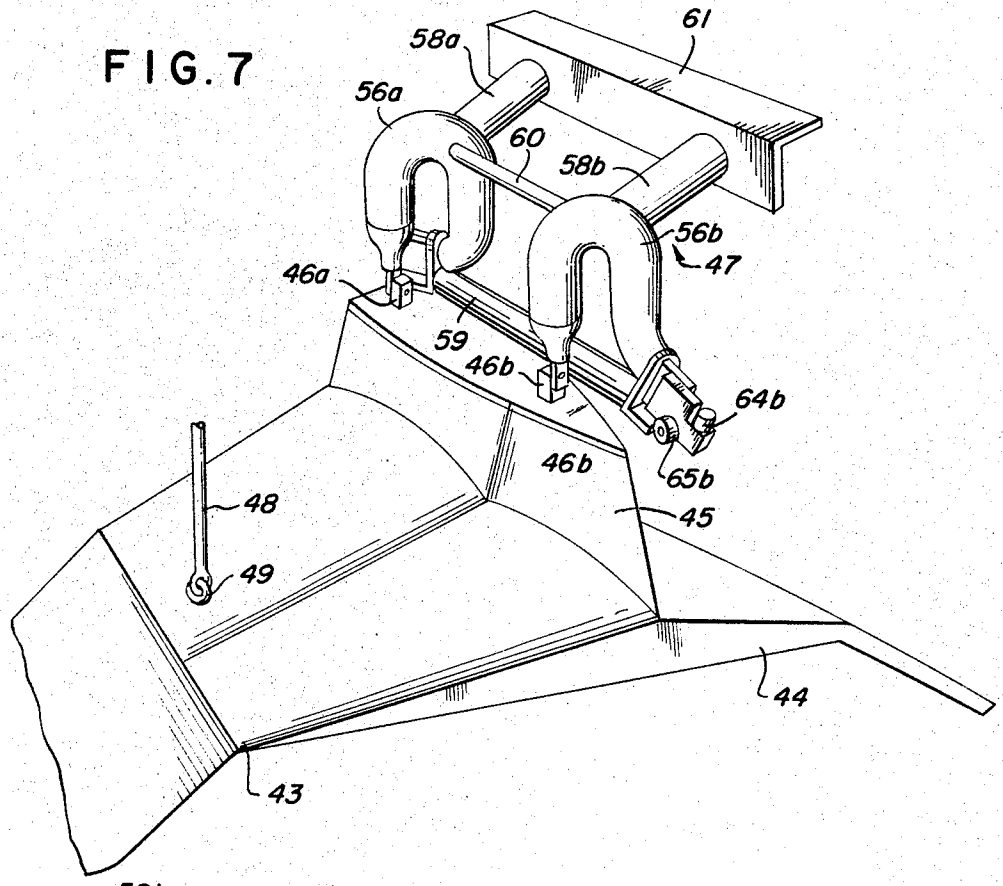
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HYDROFOIL

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FIG. 7



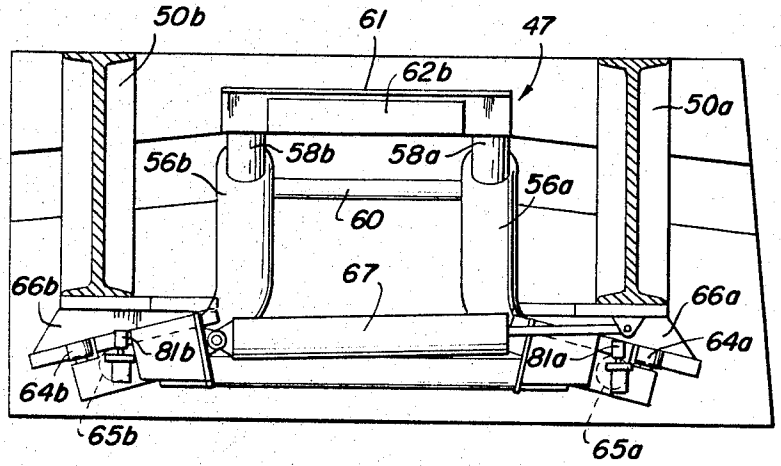


FIG. 8

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United States Patent Office 3,345,968 Patented Oct. 10, 1967

3,345,968

HYDROFOIL

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Filed Apr. 29, 1966, Ser. No. 546,243
5 Claims. (Cl. 114—66.5)

This invention relates to hydrofoil craft and in particular to hydrofoil structure.

In recent years hydrofoil operation of waterborne craft has received considerable attention, at least in part because of the speed and economy of operation offered by this mode of transportation. Commercial hydrofoil construction, however, has generally been limited to ships of small displacement and to the use of the partially submerged V-foil having a fixed attack angle. In such a foil at any given speed lift is a function of the submerged depth of the foil and control of the attack angle during flight, except by changing the attitude of the craft, is not feasible. As a consequence, the flying height of the craft is a function of speed, and the range of useful flying speeds is limited for any given craft. The partially submerged foil also suffers the disadvantage that the portions of the foil breaking the water surface, being designed to function as hydrofoils, are not properly designed to break the water surface and consequently exert drag and produce cavitation and ventilation undesirably.

These disadvantages of the partially submerged V-foil are avoided using a fully submerged, normally horizontal foil which is pivotally mounted on the lower end or ends of one or more vertical struts which are designed to break the surface of the water and, when submerged, to provide minimum drag. The fully submerged pivotally mounted hydrofoil has not seen significant commercial use, however, probably because the upward force components produced by the forward velocity of the craft with respect to the water necessary to raise the hull of the craft above the surface of the water during flying must be transmitted from the hydrofoil to the hull through one or more struts of hydrodynamic cross-section thereby producing high stress forces at points of juncture between component parts of the hydrofoil structure. The effect of such stresses upon pivot points between the strut or struts and the foil limits the load which can be transmitted from the foil to each strut. As the upward pressure of the water is exerted against the hydrofoil, the foil is also deformed producing a bending moment upon the hydrofoil which is highest at the point or points of connection of the foil with the strut or struts, tending to limit severely the permissible foil spread. When two or more struts are associated with a single foil the bending moment of the foil is transmitted through the struts to the points of juncture of the hydrofoil structure with the hull thereby exerting large stresses upon the connection joints between the struts and both the hull and the hydrofoil.

It is therefore an object of this invention to provide a fully submerged hydrofoil construction for surface watercraft in which the angle of attack can be varied during operation without the limitations imposed by the employment of one or more pivotal connections between the foil and its associated strut or struts.

It is a further object of this invention to provide a hydrofoil construction in which the effects of bending moments at the junctures of components of the foil and the rest of the foil structure are minimized and in which the transmission of bending moments to the juncture of the hydrofoil structure with the hull and superstructure are also minimized.

These and other objects of this invention are obtained utilizing a fully submerged hydrofoil construction in

which a foil is rigidly attached to the lower end of a depending strut.

In one aspect of this invention the upper end of the strut is mounted to the hull or superstructure of the watercraft for oscillatory movement in a forward and aft plane about the hydrodynamic centerline of the foil or some other desired fixed transverse line as an axis. Such an arrangement thus provides the advantages of the pivotally mounted fully submerged foil without the limitations imposed by the pivot pin carrying the load. Since the load is transmitted through relatively rigid structure to the mount for the foil structure and since the portion of the mount for the foil structure which permits the oscillatory movement to simulate pivoting can be located above the waterline, the mount can be made sufficiently heavy to take the load without the need to consider efficient hydrodynamic design for the mount. At the same time when the strut is oscillatable about the hydrodynamic centerline of the hydrofoil as an axis, changes in left produced by changes in attack angle caused by such oscillation do not result in a displacement of the location along the craft at which the lift is effectively applied to the craft. The same result is approximately achieved when the axis of oscillation of the strut is any fixed transverse line in the vicinity of the hydrodynamic centerline of the foil.

In another aspect of this invention the strut is provided with greater cross sections at its lower and upper ends than at its intermediate portion thereby to provide relatively large areas in cross section where it is affixed to the foil and to the mounting device by which it is attached to the hull or superstructure of the craft. Thus bending moments transmitted by the foil, to the extent they produce stresses in the strut, tend to flex the strut at its relatively more narrow, but jointless intermediate portion, thus reducing the strain at the joints at both ends of the strut. Since the joints are located at portions of the strut having relatively greater cross section, they are better able to resist the stresses which are applied. By proper choice of cross-sectional variation in the strut, moreover, it is feasible to locate the narrow, intermediate portion of the strut at the desired flying waterline, thus reducing to a minimum the effects of water surface disturbance by the strut.

A better understanding of the practical application of the principles underlying this invention can be obtained from the appended drawings in which:

FIG. 1 is a front elevation of a simplified hydrofoil structure in accordance with this invention before loading stresses are exerted upon it;

FIG. 2 is the same view as FIG. 1 depicting the distortions produced upon loading;

FIG. 3 is an elevation of the starboard side of a watercraft employing hydrofoils in accordance with this invention;

FIG. 4 is a fragmentary front elevation of the hydrofoil structure of the watercraft shown in FIG. 3;

FIG. 5 is a sectional taken along line 5—5 of FIG. 4;

FIG. 6 is a starboard side view of the hydrofoil structure shown in FIGS. 3 and 4 including long and short period attack angle control devices;

FIG. 7 is a perspective view of a portion of the mounting device used to attach the hydrofoil structure to the watercraft of FIGS. 3–6;

FIG. 8 is an interior elevation of the mounting device shown in FIG. 7; and

FIG. 9 is a simplified starboard side elevation of the hydrofoil structure shown in FIG. 3 etc., illustrating attack angle adjustment in accordance with this invention.

Referring more particularly to FIGS. 1 and 2, there is portrayed a simplified hydrofoil structure 10 includ-

ing a horizontal load-bearing frame **11** supported upon a horizontal hydrofoil **12** by a pair of vertical main struts **13** and **14**, the cross sections of which struts vary from greater dimensions at the ends to a smaller dimension preferably located approximately slightly below midway between the lower edge of load-bearing frame **11** and the upper edge of hydrofoil **12** and designated **15** and **16**, respectively. Frame **11** is designed to be mounted beneath a watercraft to receive the weight of the craft during flying and is mounted to be oscillated in a forward and aft direction about the hydrodynamic centerline of foil **12** as an axis, as described more fully with reference to FIG. 3 etc. The joints between frame **11** and struts **13** and **14** and between foil **12** and structs **13** and **14** are all rigid. The length of hydrofoil **12** is so proportioned that struts **13** and **14** are mounted spaced along the length of hydrofoil **12** at spacings calculated to provide an even distribution of downward forces upon hydrofoil **12** when the weight of the craft is equally distributed along frame **11**. When the external forces acting upon hydrofoil structure **10** are minimal, struts **13** and **14** and hydrofoil **12** are normally vertical and horizontal, respectively, and the tensile stresses between the junctures of struts **13** and **14** with frame **11** and with hydrofoil **12**, respectively, are negligible. However, upon loading of frame **11** during flying, the horizontal configuration of hydrofoil **12** is distorted, as depicted in exaggerated manner in FIG. 2. The uplift exerted by the sea upon hydrofoil **12** tends to apply a bending moment to the portion **17** of hydrofoil **12** lying between struts **13** and **14** while the remainder of hydrofoil **12** is subjected to a centilever action in response to the upward force of the water. The distortion produced within portion **17** of hydrofoil **12** pulls toward each other the lower ends of struts **13** and **14**, thereby imparting a bending moment within struts **13** and **14** as well as producing significant stresses at their junctures with both hydrofoil **12** and load frame **11**. Maximum deflection of struts **13** and **14** under the applied bending moments are predetermined to take place at or near the points of minimum thickness **15** and **16** thereby reducing the strain produced at the points of juncture of struts **13** and **14** with frame **11** and with hydrofoil **12**, and within most of structure **10**.

Referring more particularly to FIG. 3, a surface watercraft **20** is shown with a pair of main hydrofoil structures **21** and **21'** and a rudder assembly **22**. Hydrofoils **21** and **21'** are disposed on the starboard and port sides of craft, respectively, in side-by-side relation with their hydrodynamic centerlines on a common axis extending transversely beneath craft **20** at a position calculated to lie beneath and somewhat forward of the barycenter of craft **20** when fully loaded and at its intended flying attitude. Foils **21** and **21'** are completely symmetric with respect to a vertical plane centered on the forward aft centerline of craft **20**, and all symmetrically corresponding parts have been given the same reference numerals, except that those parts in port hydrofoil structure **21'** are distinguished from those in starboard hydrofoil structure **21** by the superscript (').

Rudder assembly **22** is similar to the main support structure and includes an upper load frame **23** and a lower foil **24**, both of which are secured to a pair of vertical rudder fins **25**, with the load frame being mounted upon the lower end of a vertical shaft **26**. The rotation of both shaft **26** and rudder **25** is controlled by a steerage lever **27** which is mounted atop of and extends perpendicular to shaft **26**. The upper section of shaft **26** remote from the foils passes slidably through the interior of a sleeve **28**, the exterior of which is received by and secured pivotally to a clamp **29** connected to the piston of a hydraulic jack **30**. The cylinder section of jack **30** is pivotally secured to the transom of craft **20** at an eye **31**. Shaft **26** at a point below sleeve **28** passes through a loose fitting collar **32**, mounted through the fantail

33 of craft **20** to which collar shaft **26** is pivotally connected by a pin **34**.

Rudder fin **25** thus can be rotated about shaft **26** as an axis to control direction in a conventional manner. At the same time under the control of jack **30**, shaft **26** can be oscillated in a forward and aft direction about pivot pin **34**, to adjust the attitude of foil **24**. Ordinarily foil **24** does not substantially contribute to supporting the weight of craft **20** and is adjustable in attitude solely for the purpose of controlling the attitude of craft **20**. Note, however, that foil carries some weight in order to give the craft stability in the event of violent pitching. Load frame **23** is larger than foil **24** and is located between the rest and flying waterlines to give minimum drag during flying operation.

Referring also to FIGS. 4 and 6, it will be noted that starboard and port main hydrofoil structures **21** and **21'** are located along the central lower portion of watercraft **20**. In view of the fact that hydrofoil structures **21** and **21'** are identical except that they are symmetric, further description of them will be confined to starboard foil structure **21** which includes a hydrofoil **40** of hydrodynamic cross section having a horizontal hydrodynamic centerline **41** extending at right angles to the forward and aft line of craft **20**. Hydrofoil structure **21** further includes a pair of struts **42***a* and **42***b*, the lower ends of which are fixedly connected to hydrofoil **40**, and the upper ends of which struts are fixedly connected to a weight-bearing structure including long and short angularly displaced sidearms, respectively, designated by reference numerals **43** and **44**, and a vertical support arm **45**.

Sidearms **43** and **44** are joined at one pair of ends at a rigid joint from which support arm **45** rises upwardly such that the assembly has the shape of an inverted Y. The remote ends of sidearms **43** and **44** are securely attached to the upper ends of struts **42***a* and **42***b*, respectively, and a brace **39** is connected between the upper ends of struts **42***a* and **42***b* to which it is securely affixed at its ends, such that hydrofoil structure **21** effectively is a rigid structure.

A pair of bosses **46***a* and **46***b* mounted atop vertical support arm **45** provide connection terminals respectively through which the weight of craft **20** is in part placed on foil structure **21**.

An elongated rigid rod **48**, the upper end of which is supported by the superstructure of craft **20** is secured to hydrofoil support **21** at its lower end at eye **49** mounted atop horizontal sidearm **43** intermediate its ends. Rod **48**, which can be employed to raise or lower the hydrofoil support dependent upon the mode of operation desired, provides a point at eye **49** on which the weight of craft **20** is in part placed on foil structure **21**. While rod **48** is preferably adjustable in length to permit exact control of the position of hydrofoil **40** in relation to craft **20**, a rod of fixed length can also be utilized.

As may be more clearly seen from FIG. 7, a pair of tubular, inverted U-shaped fittings **56***a* and **56***b* is rigidly secured in spaced relation to form a mounting device **47** by means of tubular horizontal braces **59** and **60**. Frame **47** acts to transmit the weight of craft **20** to hydrofoil structure **21** through cams **66***a* and **66***b* which are secured to I-beams **50***a* and **50***b*, respectively, mounted transversely of the hull of craft **20**. There is also a protective shield **57** for an aperture in the hull through which a portion of frame **47** passes. The outboard ends of U-shaped fittings **56***a* and **56***b* taper to centrally apertured rectangular terminals which are bolted to bosses **46***a* and **46***b* on hydrofoil structure **21**, while the inboard ends of U-shaped fittings **56***a* and **56***b* flair into tangential connection with tubular brace **59** to the ends of which they are affixed.

A beam **61**, secured to the upper portions of fittings **56***a* and **56***b* by a pair of supports **58***a* and **58***b*, respectively, supports a pair of spaced plates **62***a* and **62***b* on

its interior, shipboard side with the plates parallel and defining between them a horizontal slot extending in a fore and aft direction. A cylindrical roller **63** is mounted secured to I-beams **50***a* and **50***b* in craft **20** for rotation about its axis in a vertical position in the slot between plates **62***a* and **62***b*. The diameter of cylinder **63** is less than the spacing of plates **62***a* and **62***b*, the function of cylinder **63** being to limit inboard and outboard movement of frame **47**, but not to guide it.

The junction of the inner ends of fittings **56***a* and **56***b* with the ends of brace **59** are constructed as mounting points for a pair of cam followers **64***a* and **64***b*, respectively, and for a pair of rollers **65***a* and **65***b*, respectively. Cam followers **64***a* and **64***b* are mounted projecting outwardly of the inner ends of fittings **56***a* and **56***b* for rotation about horizontal axes extending transversely of craft **20**, while rollers **65***a* and **65***b* are mounted above the position of cam followers **64***a* and **64***b* for rotation about axes in a common fore and aft vertical plane which are canted oppositely such that such axes intersect on any desired transverse line located below the flying waterline of craft **20**, preferably on the hydrodynamic centerline of foil **40**, as illustrated.

Cams **66***a* and **66***b* in the form of wedge-shaped plates are mounted exteriorly of the hull on the ends of I-beams **50***a* and **50***b*, respectively, beneath an aperture in shield **57** through which fittings **56***a* and **56***b* pass in such a position that the undersurfaces of cams **66***a* and **66***b* bear against the upper sides of followers **64***a* and **64***b*, respectively, and such that rollers **65***a* and **65***b*, respectively, bear against the inner lower edges of cams **66***a* and **66***b*. The undersurfaces of cams **66***a* and **66***b* in contact with followers **64***a* and **64***b* are oppositely inclined with the same angle of inclination and are perpendicular to planes including the hydrodynamic centerline **41** of foil **40** or to such other transverse line about which it is desired to cause foil **40** to oscillate in adjusting its attitude. A hydraulic jack **67** is secured between I-beam **50***a* and the junction of fitting **56***b* and brace **59** in such a manner that frame **47** can be moved in a fore and aft direction by jack **67**. It will be apparent that foil structure **21** hangs as a dead weight when craft **20** has no forward motion with respect to the water. Under such circumstances followers **64***a* and **64***b* fall free of cams **66***a* and **66***b*, and rollers **65***a* and **65***b* similarly move away (inwardly) from the cams. If such movement is not otherwise limited by the geometry of the device stops must be provided to perform such function. Plates **80***a* and **80***b* can thus be mounted beneath cams **66***a* and **66***b* to limit downward movement of followers **64***a* and **64***b*, and roller stops **81***a* and **81***b* can be mounted on frame **47** to limit inward movement by contact with plates **82***a* and **82***b*, respectively, mounted inwardly of stops **81***a* and **81***b*.

Referring to FIG. 9, which shows in simplified manner the relationship between foil structure **21** and inclined cams **66***a* and **66***b*, it will be seen that the undersurfaces of cams **66***a* and **66***b* are tangent to an arc having as a center the intersection of the plane of the drawing with hydrodynamic centerline **41** of foil **40**. It will also be seen that for limited distances in the vicinity of cam followers **64***a* and **64***b* the undersurfaces of plates **66***a* and **66***b* approximate such arc. As a consequence, as frame **47** is moved in a forward or aft direction, foil structure **21** oscillates about hydrodynamic centerline **41** as an axis. Rod **48** is pivotally connected to the superstructure of craft **20** to accommodate such movement of foil structure **21**. Hydrofoil **40** can thus be changed in attitude with respect to craft **20** while no change occurs in the location along craft **20** in the point of application of the lift produced by forward movement of foil **40** through the water. The same result is approximately achieved when the interrelation of the geometrical configurations of the contacting surfaces of the cam followers and plates are dimensioned such that the axis of oscillation of struts **42***a* and **42***b* is any fixed transverse line in the vicinity of hydrodynamic centerline **41**.

Side arms **43** and **44** are generally hollow and have cross sections terminating with a pointed leading edge **68** to provide a minimum of resistance to the forward motion of craft **20** at takeoff and from waves which may from time to time break over foil structure **21** during flight. The interiors of side arms **43** and **44** are preferably filled with a commercially manufactured buoyant foam **69**, e.g. polyurethane, to reduce the effect of water seepage, and vertical braces are provided within horizontal side arms **43** and **44** to increase the load-bearing ability of each member.

Both the width and thickness of main struts **42***a* and **42***b*, which are of hydrodynamic design to minimize drag, are tapered from greater cross sections at both ends of each to a smaller cross section designated **70***a* and **70***b*, respectively, intermediate the ends, and struts **42***a* and **42***b* are solid bronz castings. Hydrofoil **40** is of uniform cross section and suitable hydrodynamic design to provide the required lift to support the weight of craft **20** at design speed with minimum drag. Foil **40** is preferably formed with a stainless steel skin supported on steel strength members with voids filled with rigid foam, such as polyurethane foam. It will be apparent that foil structure **21** functions in the manner described with reference to foil structure **10** described in FIGS. 1 and 2 to absorb bending moments in flexure of struts **42***a* and **42***b* to reduce the strain imposed on the joints between component parts of structure **21**.

In operation, watercraft **20** is driven by a suitable propulsion arrangement, for example, by a power driven screw **71** located beneath fantail **33**. After craft **20** has attained adequate speed without flying and with foils **40** and **40'** at an attitude presenting a low or non-existent attack angle, lift for takeoff is developed by oscillating foil structures **21** and **21'** counterclockwise, as seen in FIG. 3, to provide a positive attack angle. Rudder assembly **22** at the same time can be oscillated slightly by moving the upper end of shaft **26** forward to increase the attack angle of foils **40** and **40'** by changing the attitude of craft **20** as well. As flying height is obtained, these procedures are reversed to level craft **20** off. Preferably at flying height screw **71** is about half-submerged, and the water surface breaks at narrow portions **70***a* and **70***b* of foil structure **21** and at the corresponding portions of foil structure **21'**. It will be appreciated that flying height is thereafter maintained by adjusting rudder assembly **22** for proper fore and aft trim and by adjusting foil structures **21** and **21'** together to maintain height and oppositely to adjust transverse trim.

Automatic control of the attitude of hydrofoils **40** and **40'** is not only feasible but desirable. To this end in FIG. 6 there is illustrated a float **72** attached pivotally to the lower end of a rod **74** slidably received in the lower end of a sleeve **73** secured to craft **20** aft of foil structure **21** and **74**. The extension of rod **74** in sleeve **73** indicates the position of float **72** and hence locates the waterline in flight. A control mechanism of conventional nature corrects the attitude of foil **40** by means of jack **67** to reciprocate frame **47** in a forward and aft direction. The control mechanism should be damped to provide a slow, i.e., long period, correction to a desired flying height. Additionally a sensor foil **77**, attached to a strut **76** at its lower end so as to follow a stream line path and thereby indicate the direction of movement of craft **20** in the water is suspended immediately in front of foil **40** to provide control the attitude of foil **40** to maintain a constant angle of attack in a short period control system such as described in Patent No. 2,773,467.

I claim:

1. In combination:

(a) a watercraft,

(b) a hydrofoil structure including

(i) hydrofoil having a hydrodynamic centerline and

(ii) strut means having said hydrofoil secured rigidly thereto, and

(c) mounting means on said watercraft supporting said strut means with said hydrofoil in a fully submerged position to provide a lifting component along said hydrodynamic centerline when said craft has forward velocity across the surface of a body of water, said mounting means including

(i) means for oscillating said hydrofoil structure relative to said craft about a fixed transverse axis in the vicinity of said hydrodynamic centerline.

2. The combination according to claim 1 in which said means for oscillating said hydrofoil structure includes cam means having a cam surface approximating an arcuate surface centered on said transverse axis.

3. The combination according to claim 2 in which said cam means includes

(a) a pair of inclined plates the undersurfaces of which define a pair of said cam surfaces and

(b) a pair of cam followers riding against said undersurfaces,

said plates being affixed to said watercraft and said followers being mounted on said hydrofoil structure.

4. The combination according to claim 1 in which said strut means includes

(a) a pair of struts, spaced apart and each rigidly secured at the lower end thereof to said hydrofoil, and in which said hydrofoil structure further includes

(b) a load-bearing frame rigidly secured to the upper ends of said struts,

each of said struts being of greater cross section at the ends thereof than at an intermediate portion thereof, and said mounting means being associated with said load-bearing frame to support said strut means as aforesaid.

5. A hydrofoil structure including:

(a) a hydrofoil adapted to be fully submerged,

(b) a pair of struts spaced apart and rigidly secured to said hydrofoil at the lower ends of said struts,

(c) a load-bearing frame rigidly secured to the upper ends of said struts, and

(d) mounting means associated with said load-bearing frame adapted to support said structure, each of said struts being of greater cross section at the ends thereof than at an intermediate portion thereof.

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