

[54] **HYDROFOIL FOR WATERCRAFT WITH
LIFT GENERATION THROUGH AIR
SUPPLY OF THE FOIL UNDERSIDE**

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[58] **Field of Search** **114/66.5 H;**
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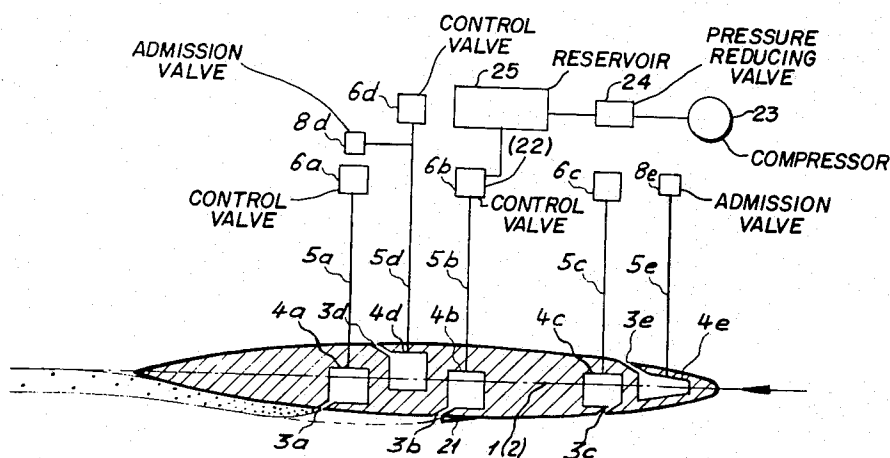
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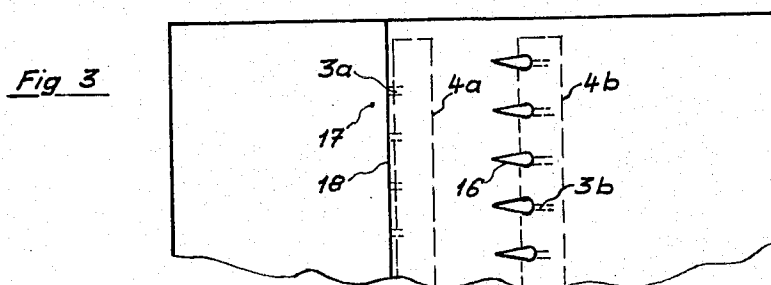
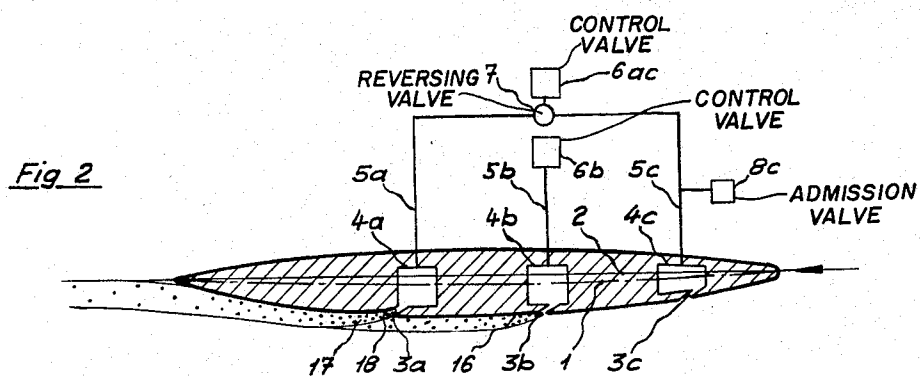
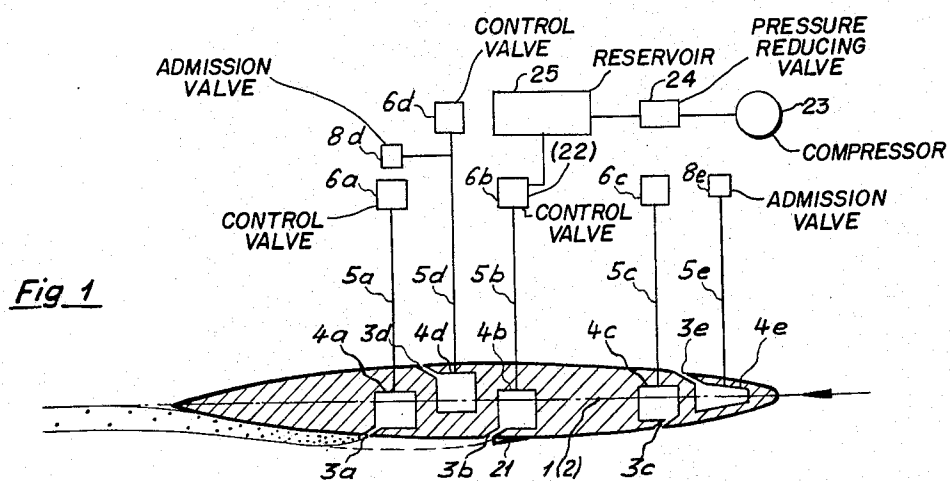
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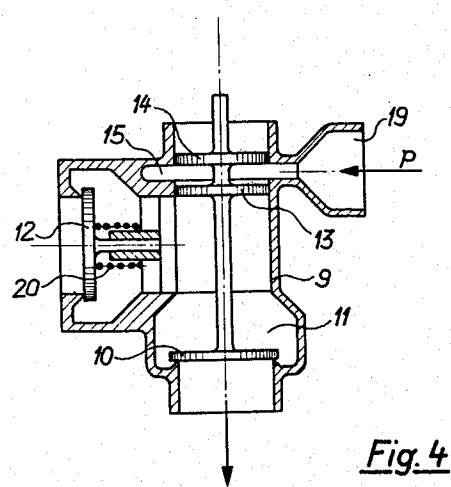
ABSTRACT

A hydrofoil for watercraft, the lift of which can be influenced through the admission or feed of a controllable quantity of air to the subpressure or underpressure region of the foil profile and which possesses air exit openings which extend in the span width direction of the foil. The foil profile possesses an approximately linear mean line, so that with chord-parallel flow there at most occurs an insufficient lift and for generating sufficient lift the under side of the foil profile is supplied with air, the quantity of which can be varied for the purpose of regulating lift.

8 Claims, 4 Drawing Figures







HYDROFOIL FOR WATERCRAFT WITH LIFT GENERATION THROUGH AIR SUPPLY OF THE FOIL UNDERSIDE

BACKGROUND OF THE INVENTION

The present invention relates to a new and improved construction of hydrofoil for watercraft which can attain high speeds free of cavitation.

It is well known that so-called sub-cavitating foils hardly can exceed speeds of 60 knots, because then it is no longer possible to avoid extensive cavitation. Due to this phenomenon the resistance is markedly increased and limitations are placed upon the controllability of lift, for instance by changing the angle of attack or through the action of a pivotable foil flap. The stability of a vehicle with completely immersed foils can be, however, only maintained by automatic variations in the lift, which, for instance, can be controlled by a depth sensor in a restoring sense. A damaging side effect of cavitation resides in the erosion of the material of the foil occurring by virtue of the impact of the water which arises upon collapse of the cavitation bubbles.

The problem which is encountered in maintaining the foil free of cavitation resides in maintaining the excess speeds at the foil profile and the therewith associated pressure drops as small as possible so that the absolute pressures remain above the vapor pressure for the prevailing water temperature. This can be realized with the known profile contours of small camber (i.e. thin profiles) with as rectangular as possible pressure distribution and small lift coefficient (C_a). However, at speeds exceeding 60 knots there measures lead, on the one hand, to such small profile thicknesses that such no longer are capable of withstanding the tensile loads and, on the other hand, result in such small lift coefficients that the lift-drag ratios (C_w/C_a) assume impermissibly high values. Owing to the small lift coefficients the sensitivity to changes in the flow angle, which occur in the seaway owing to the orbital motion in the water, become extremely large, impairing the seaworthiness of the watercraft.

Attempts have been made to overcome these difficulties through the use of so-called "base-ventilated" foils. Such possess foil profiles with a blunt rear edge, whereby with the same thickness ratio as a standard, sub-cavitating foil, there occurs a flatter camber of the upper side and therefore a reduction in the local excess speeds or velocities. Consequently, up to higher speeds than with conventional foils the foil remains cavitation free. In order to reduce resistance the blunt rear edge of the profile is vented via the blunt rear edge of the struts. Such foil is, however subject to dangerous sudden lift collapse effects when the infed air penetrates from the rear at the suction side of the foil profile during pronounced increase of the angle of attack. It is for this reason that such solution has not found any practical application.

SUMMARY OF THE INVENTION

Hence, it is a primary object of the present invention to provide a new and improved construction of hydrofoil for watercraft which is not associated with the aforementioned drawbacks and limitations of the prior art proposals.

Another and more specific object of the present invention aims at overcoming the above-discussed problems through a completely novel principle of generating lift of the hydrofoil so as to extend the point where cavitation occurs to high speeds, to reduce the resistance and to decrease the sensitivity to changes in the flow angle.

Now in order to implement these and still further objects of the invention, which will become more readily apparent as the description proceeds, the invention contemplates that the foil profile possesses an approximately linear mean line, so that with flow parallel to the chord of the foil there occurs at best an insufficient lift and for generating sufficient lift a controllable air quantity is admitted from the atmosphere through exit openings to the underside of the profile at its under pressure region.

The lift at this approximately symmetrical bi-convex profile thus occurs with chord-parallel flow, due to reduction in the suction force at the foil underside through the air feed, so that the under pressure over the upper surface, or the difference between the under pressure across the upper surface and the under pressure which still prevails across the underside of the foil generates the lift. In so doing, the lift can be randomly varied by changing the admitted or infed quantity of air (dosing by means of valves) in a manner such that the lift increases with increasing quantity of air and decreases with decreasing quantity of air. The upper surface of the profile can have a small camber with as rectangular as possible pressure distribution, so that only small excess speeds occur, without the profile thickness becoming insufficiently small as concerns its strength characteristics, because the foil underside which has become at least partially ineffectual by virtue of the air feed, approximately doubles the profile thickness with its camber height.

Further, to additionally prevent the formation of cavitation the foil preferably contains exit rows at the upper or top surface, to which there is then only admitted an automatically controlled quantity of air or a quantity of air which is controlled by a sensor when the flow angle increases.

The advantage of the new technique for generating lift however not only resides in the fact that excess speed at the suction side can be maintained small, notwithstanding a sufficient profile thickness, similar to the situation of the base-ventilated foil, but also that there are realized a whole spate of further advantages of notable significance, which will be considered hereinafter:

1. Due to the air feed of the underside by means of air admission from the atmosphere there occurs a considerable reduction in the profile resistance. This could be proven by tank tests. Consequently, it is possible, in contrast to the conventional wetted foil sections to reduce the lift coefficient, without being confronted with poor lift/drag ratios, whereby again it is possible to approach higher velocity regions. Furthermore, the stresses at the foils remain within tolerable limits owing to the lower surface loads.

2. As has been established by trials in cavitation tanks at lower cavitation values the lift gradient ($dC_l/d\alpha$) is reduced by virtue of the air feed and can almost amount to zero with the feed or supply through exit openings located at the front portion of the profile, that is to say, the foil hardly responds to changes in the

angle of attack. This is so because at the underside the suction force and therefore the outflowing quantity of air increases with decreasing angle of attack (lift increase) and the lift losses are partially or completely compensated, whereas with increasing angle of attack the reverse occurs. Hence, there is present an automatic lift control having the effect of a reduction in the lift gradient.

The reduction in the lift gradient is of decisive importance for the behavior in the seaway, because thereby the influence on lift due to the orbital motion in the waves is lessened or completely overcome. The changes in the flow angle of the hydrofoil, arising due to the movement of the water particles, constitutes the greatest problem with respect to the seaworthiness of the hydrofoil boat or vehicle in a following sea. When the boat has departed from the wave front the lift of the foil by the upwardly directed components of the orbital velocity is increased, so that it tends to emerge from the wave valleys in order to then break low into the following wave ridge, where the orbital component is downwardly directed. Although the change in the flow angle at the foil in the seaway decreases proportional to the velocity, high speed boats owing to their small lift coefficient, are markedly influenced by the orbital velocity, so that the reduction of the lift gradient assumes increased significance with the increase in speed.

In order to compensate changes in lift at conventional foils, which occur owing to a change in the flow angle, the foil must be pivotably mounted and automatically controlled with regard to the flow angle such that it adjusts itself approximately in the flow direction. This constitutes a considerable expenditure since, apart from the pivotal mounting of the foil, there must be provided a sensor which responds to the flow direction, and which delivers its commands to a hydraulic actuation mechanism which again brings about pivotal movement of the foil. The advantages of the foil of this development therefore should be quite clear.

3. Just as the known hydrofoils, the lift of which is generated by camber of the mean line and inclination of the profile chord at a positive angle with respect to the flow direction, the foil of the invention with air fed on the underside during approaching the water surface or level in conventional manner experiences a reduction in lift due to the surface effect, having a self-stabilizing action. The foils which are air-fed at the upper surface of the foil exhibit a small lift increase as they approach the water surface, so that the immersion depth control is rendered more difficult and the danger of breaking through the water surface with complete destruction of lift due to air entry over the entire foil is increased.

The inventive foil is accordingly considerably easier to stabilize than conventional fully wetted foils and foils which are air-fed at the upper surface of the foil, owing to its small lift gradient and the more favorable action of the surface effect.

Finally, the foil with lift generation through supply at the pressure side generally affords the advantage in contrast to the conventional fully wetted foils, that the air feed or supply can be simultaneously employed for controlling lift, whereby the difficult pivotal mounting of the foil for the purpose of changing the angle of attack, or pivotably mounted flaps at the foil rear edge and its hydraulic adjustment mechanism, can be dispensed with.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will be better understood and objects other than those set forth above, will become apparent when consideration is given to the following detailed description thereof. Such description makes reference to the annexed drawings wherein:

FIGS. 1 and 2 respectively illustrate embodiments of hydrofoils in sectional view with their air channels or ducts and exit openings, the air valves with the infeed lines having only been schematically depicted;

FIG. 3 is a plan view of a portion of the foil depicted in FIG. 2; and

FIG. 4 schematically illustrates in sectional view a regulating or control valve with overpressure supply.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Describing now the drawings, FIGS. 1 and 2 illustrate embodiments of two foil sections equipped with the inventive system for generating lift. The direction of flow has been illustrated by the depicted arrow of each Figure. In FIG. 1 the mean line 1 is a straight line having a symmetrical, bi-convex droplet shape which possesses at both sides a conventional contour with uniform lift distribution (for example NACA 16 series type), so that with the illustrated chord-parallel flow (the chord 2 coincides with the mean line 1) there does not occur any lift. Lift only then occurs when air is sucked from the free atmosphere out of the air exit opening 3 (i.e. the openings 3a-3c of FIG. 1 and 3a-3c of FIG. 2), through the negative pressure at the underside of the foil and there is thus decreased the magnitude of the negative pressure. The air is delivered to these exit openings 3 by the ducts or channels 4 (i.e. the ducts 4a-4c of FIG. 1 and 4a-4c of FIG. 2) which are connected with corresponding conduits or channels 5 (i.e. channels 5a-5c of FIG. 1 and 5a-5c of FIG. 2), here only schematically indicated by a line, at the struts. These channels 5 are operatively connected by the schematically depicted regulating or control valve 6 (i.e. valves 6a, 6b, 6c of FIG. 1 and 6ac, 6b of FIG. 2) with the free atmosphere. The valves 6, which also can be arranged directly at the inlet to the channels 4, regulate the inflow of the quantity of air and are controlled in turn by sensors which respond to the movement of the vehicle.

With undisturbed travel speed the foil underside is supplied with a quantity of air which brings about approximately one-half of the maximum lift and which maintains the vehicle weight in equilibrium, so that the lift can be increased by increasing the quantity of air and can be reduced by reducing the quantity of air, in both directions to the same extent. The maximum lift is attained by the quantity of air which saturates the foil (in other words at the point where increasing the air quantity has no further effect), and the smallest lift with shut-off air feed, whereby the lift with chord-parallel flow becomes null.

In the embodiment of FIG. 1 there are provided at the underside of the foil three exit rows 3a, 3b and 3c, which extend completely or partially over the span width of the foil and which receive air via the associated ducts or channels 4a, 4b and 4c respectively. The infeed of one-half of the air quantity can occur simultaneously through all of the air exit openings 3a, 3b and 3c or through individual ones thereof or a row, whereby

then the other rows can be switched-in for the purpose of increasing lift.

The position of the air outflow has an influence upon the lift gradient, that is to say, also upon the lift changes, which occur as a function of the changes in the angle of attack. The lift gradient is smaller when air exit occurs at the front profile underside and is larger when the outlet openings are located at the rear profile underside. This phenomenon can be explained in terms of the pressure changes which occur at the foil profile during variation of the angle of attack and which are most pronounced at the region of the front edge, so that also at that location the sucked-up air quantities vary most markedly in the sense of a gradient reduction or compensation of the effect of the angle of attack.

Since during travel in a following sea there is desired as small as possible gradient, whereas for a course against the sea the orbital speed strives to help the vehicle or craft over the tops of the waves and therefore, depending upon wave length, response to angle of attack changes to a greater or lesser extent is desirable, the invention contemplates a reversibility of the control from a rear to a front exit and vice versa. Thus, for instance, there can be switched-in the air feed or supply through the exit opening 3a for travel directions against the sea and air feed through the opening 3c for travel directions with the sea, and specifically, with a quantity of air which produces one-half of the maximum lift. To increase the lift there is then switched-in, for instance, the air exit row 3b, shortly prior to reaching saturation through the rows 3a or 3c respectively.

The apparatus for carrying out the reversal or switching operation between a front and rear exit row can be constructed, for instance, as depicted in FIG. 2, such that both rows can be controlled from the same regulating or control valve 6ac and that an electrically operated reversing valve 7 which is controlled as a function of the control status or condition selectively releases the flow path to the desired duct or channel 4a or 4c.

Also by supplying the upper surface of the foil profile by means of an exit row which is situated at the region of the head of the foil profile, it is possible to attain a reduction in the lift gradient. Trials have however shown that such configuration is practically non-usable, because there then occur impermissibly high auxiliary resistances and the lift is markedly increased in an extremely dangerous manner when approaching the water surface.

For further safeguarding the foil against cavitation and compensating for increases in lift, which can arise with large positive flow angles due to the orbital motion in the seaway, after the air feed at the underside or lower side of the profile has already been completely closed, there are also provided at the upper surface of the profile air exit openings 3d and 3e to which there is first admitted air when the flow angle or lift is increased. The rear row 3d depicted in the exemplary embodiment of FIG. 1 serves for control purposes, whereas the row 3e serves to counteract cavitation. This row, as taught in my copending commonly assigned U.S. application, Ser. No. 366,795 filed June 4, 1973, and entitled "Automatic Mechanism For Preventing Cavitation At Air-Fed Hydrofoils And Flow Bodies" is arranged at the location where there occurs the maximum excess speeds and is connected with an automatically opening admission valve 8e which opens shortly prior to occurrence of the cavitation pressure.

The exit row 3d is also preferably placed at a second location of the greatest excess speed occurring during small angles of attack and, apart from the control valve 6a, is also coupled with an admission valve 8d according to the teaching of the aforementioned application.

In the exemplary embodiment of FIG. 2 the mean line 1 of the foil profile is slightly domed towards the bottom, so that with chord-parallel flow there occurs a slight negative lift. Consequently, the camber of the upper surface of the foil profile becomes flatter which favors extending cavitation into higher speed ranges. Lift also occurs in this instance with chord-parallel flow only upon admission of air to the foil underside. The supply or feed of that quantity of air which results in approximately one-half of the maximum lift, occurs in this case for instance conjointly through the outlets or exits 3a and 3b. It should be readily apparent that with the profile form of the embodiment of FIG. 2 air exit rows 3 also can be provided at the upper surface of the foil corresponding to the arrangement of FIG. 1.

In order to counteract the occurrence of cavitation at the underside with negative flow angles, there is here depicted an automatic admission valve 8c for the air exit row 3c, as taught in the above-mentioned application, whereby the exit row 3c is placed at the location of maximum excess velocity with negative flow angles.

The maximum lift also can be increased if the exits at the underside have air delivered thereto at an excess pressure instead of at atmospheric pressure. The required excess pressure air quantity can be generated by a blower or compressor 23 (FIG. 1) which is coupled with the drive equipment, or which can be drained off from the last stage of the compressor of a gas turbine, if such a propulsion engine is provided. Because the delivered air pressure of the mentioned compressors is usually quite high and a pressure of only about 1 at = 14.2 lb/in² is advantageous for foil feeding, the compressed air is led through a pressure reducing valve 24 and then accumulated in a reservoir 25. Since the excess pressure or overpressure feed occurs only briefly, air is supplied intermittently from the reservoir and the air requirement remains very small.

Any of the outlet rows 3 can be fed with overpressure, but with an arrangement of a number of exit rows one behind another, preferably only a row placed in front of another is charged with overpressure i.e. row 3b or/and 3c in the Figures. In FIG. 1 exit row 3b is fed with overpressure as an example. In this case the air inlet valve 6b admits compressed air only, but is operated such that it opens first when the foil is almost saturated by the rows situated therebehind. In a different technique with a lower consumption of compressed air the control valve 6b can be replaced by the valve which is depicted in FIG. 4 and which is then numbered 22 in FIG. 1. This valve is constructed in such a way that in the opening direction during a first phase it admits air at atmospheric pressure until a valve outlet area is attained by which the foil is almost saturated, and then during a second phase admits a quantity of air which is at excess pressure.

FIG. 4 schematically illustrates an example of such control or regulating valve. In the valve housing 9 there is arranged a valve plate 10 which is actuated by the sensors and which valve plate 10 controls the through-passage or flow in the foil from the chamber 11 to the associated channel or duct 4. This chamber receives its air inflow or supply from the atmosphere by the check

valve 12. The valve plate 10 is coupled with a slide valve means 13/14 which controls throughflow from an annular chamber 15, which is charged by component 19 with excess or overpressure p , to the compartment 11. When the valve plate is opened for the most part and the slide element 13 has moved past the lower edge of the annular compartment 15 then compressed air can flow into the compartment or chamber 11. As soon as the pressure in this compartment has risen by a small amount then the spring 20 closes the check valve 12 and the associated channel 4 is now charged with overpressure for such time until the slide valve again closes the connection from the excess pressure infeed 19 to the compartment 11.

It should be readily understood that a random number of air exit rows can be provided at the profile underside and the profile upper side and that also the exit openings at the upper side can be charged with excess pressure in the described manner.

By virtue of an advantageous construction of the air exit openings, which can be in the form of bores or slots, it is possible to influence the action of the feed or supply and the resistance. Advantageous constructional forms have been depicted in FIGS. 2 and 3. As can be recognized by referring to FIG. 2 and also FIG. 1 these bores are inclined towards the rear. The exit 3b of FIG. 2 and FIG. 3 has a shell-like milled portion 16 behind the bore in order to obtain a smooth air outflow tangentially with respect to the foil surface. Even more advantageous is the outflow or exit 3a, at which there is provided a groove 17 which extends in the span width direction, the front portion of which possesses a low almost vertical wall 18 at which the bores open and the rear portion of which merges in a continuous curve into the profile contour. With this constructional embodiment the air does not depart in individual jets, as is the case for exit 3b, rather it can expand within the groove transverse to the direction of travel, so that the air leaves the groove in the form of a closed veil or film, thereby attaining the lowest resistance. In the event that a slot is provided as the outlet or exit, then the outlet mouth is formed in analogous manner. The described constructions for the air exits are employed both at the underside as well as the upper side of the foil profile.

In order to increase the suction force at the air exit rows at the underside of the foil profile, it is possible, as depicted in FIG. 1, to arrange in front of the exit rows a wedge or stepped portion 21 which extends at least partially over the span width and over the contour of the foil profile, this wedge or stepped portion extending with a blunt portion towards the rear and having a flat starting portion extending towards the front.

The foil which is designed according to the invention, for the reasons to be explained hereinafter, is particularly suitable for vehicles operating at high speeds. Apart from the fact that the foil can attain high speeds of velocities without cavitation, it has been found through experimentation that the air feed or supply with respect to the occurring resistance becomes that much more favorable the greater the speed. Furthermore, there increases the effectiveness of the air control, which can be expressed in terms in relation to the ratio $\Delta C_L / C_L$, i.e. the attainable lift variations of the average lift, with speed, because the value of C_L becomes smaller with increasing speed.

The mean line of the foil profile, which according to the invention and as a prerequisite for a weakly cambered upper surface, at most generates an insufficient lift, can possess a random curved shape, for instance can be approximately parabolically curved or curved in a S-shape. For high velocities or speeds exceeding 60 knots the thickness ratio of the profile is considerably smaller than illustrated in the drawings.

It should be further understood that the novel foil of this development also can be employed for other purposes than for hydrofoil boats, for instance as a starting aid for hydroplanes.

While there is shown and described present preferred embodiments of the invention, it is to be distinctly understood that the invention is not limited thereto, but may be otherwise variously embodied and practiced within the scope of the following claims.

What is claimed is:

1. System for generating lift at a hydrofoil for watercraft, the hydrofoil having air exit openings extending in the span width direction thereof, the lift of said hydrofoil being influenced by the admission of a controllable quantity of air to the negative pressure region of the hydrofoil through said air exit openings, the improvement comprising said hydrofoil profile having an approximately linear mean line such that chord parallel flow generates insufficient lift to support the weight of said watercraft, means for generating sufficient lift to support the weight of said watercraft, said lift generating means comprising said air exit openings being located on the underside of the foil profile, a wedge positioned forwardly of said air exit openings and extending to a point below the profile of said hydrofoil, said wedge having a rearwardly directed blunt edge, means for continuously supplying a quantity of air to said air exit openings and means for varying the quantity of air admitted to said air exit openings for regulating the lift.

2. The system as defined in claim 1, wherein the air supplying means supplies the undersides of the hydrofoil, at undisturbed cruising speed, with a quantity of air equal to approximately one-half of the air quantity supplied for maximum lift.

3. The system as defined in claim 1, wherein the underside of the hydrofoil is provided with a plurality of rows of air exit openings arranged in spaced relation transversely of the span width direction of said hydrofoil and means for selectively switching the air supply between a forwardly and rearwardly disposed row of air exit openings in order to change the lift gradient.

4. The system as defined in claim 1, wherein air exit openings provided at locations of the maximum prevailing excess speeds, and means including an automatic admission valve for feeding air to such air exit openings when the vapor pressure of the water has almost been attained.

5. The system as defined in claim 1, wherein a groove extends at least over a part of the span width of the foil at least some of the air exit openings communicating with said groove, the front portion of the groove being formed by an almost vertical wall whereas the rear portion extends into the contour of the profile in a continuous curve.

6. The system as defined in claim 1, further including means for delivering air at excess pressure to the air exit openings and at least one valve means for regulating the air admission, constructed such that in the opening direction during a first phase said valve means,

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admits air under atmospheric pressure until a valve outlet area is attained by which the foil is almost saturated, and during a second phase said valve means admits air which is at excess pressure.

7. The system as defined in claim 1 wherein said means for continuously supplying air to said air exit openings includes means for supplying atmospheric air and means for supplying air at excess pressure, and further including valve means operatively connecting said excess pressure air supplying means and said atmospheric air supplying means with said air exit openings for delivering atmospheric air to said air exit openings until the hydrofoil is almost saturated and thereafter

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delivering excess pressure air to said air exit openings.

8. The system as defined in claim 7, wherein said valve means comprises a compartment containing a valve plate for regulating a throughpassage from the compartment to the hydrofoil, a check valve having an open and a closed position and connecting said compartment with said means for supplying atmospheric air, a slide valve means operatively coupled with said valve plate and connecting said compartment with said means for supplying excess pressure air for admitting excess pressure air to said compartment when the valve plate has almost attained its maximum open position.

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