US 20050076819A1

(19) United States

(12) Patent Application Publication (10) Pub. No.: US 2005/0076819 A1

Hilleman (43) Pub. Date: Apr. 14, 2005

(54) APPARATUS AND METHOD FOR REDUCING HYDROFOIL CAVITATION

(76) Inventor: **Terry Bruceman Hilleman**, Marshalltown, IA (US)

Correspondence Address:
MCKEE, VOORHEES & SEASE, P.L.C.
801 GRAND AVENUE
SUITE 3200
DES MOINES, IA 50309-2721 (US)

(21) Appl. No.: **10/682,174**

(22) Filed: **Oct. 9, 2003**

Related U.S. Application Data

(60) Provisional application No. 60/417,127, filed on Oct. 10, 2002.

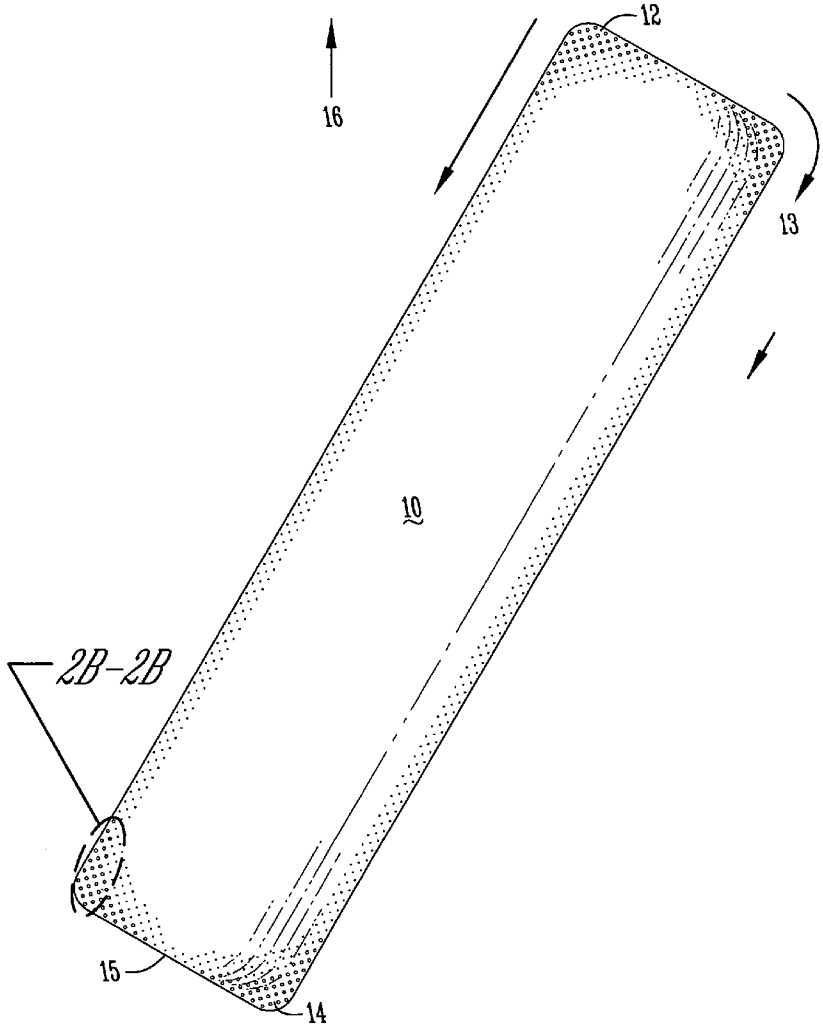
Publication Classification

(51) Int. Cl.[7] **B63B 1/34**

(52) U.S. Cl. .... **114/67 R**

(57) **ABSTRACT**

A method of reducing underwater hydrofoil cavitation is described; hydrofoil steering vanes trade a small degree of efficiency for significant cavitation reduction, through perforations in the hydrofoil. Some pattern examples are discussed. A method of further cavitation reduction through surface texture variation also reduces underwater hydrofoil drag; some patterns are discussed. Combining the methods provides maximum cavitation reduction.



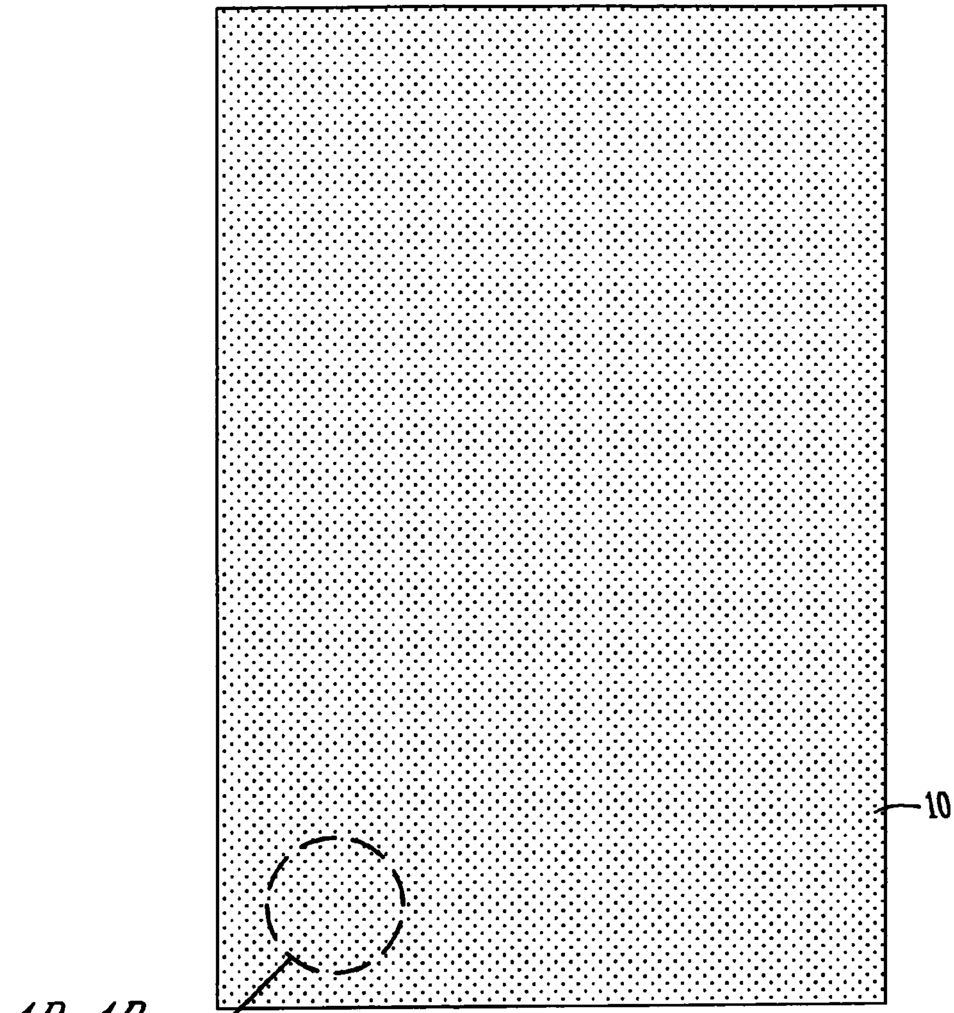


Fig. 1A

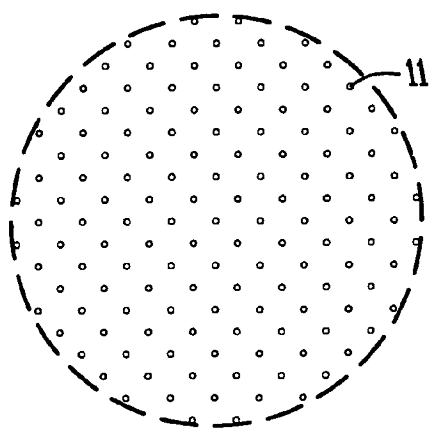


Fig. 1B

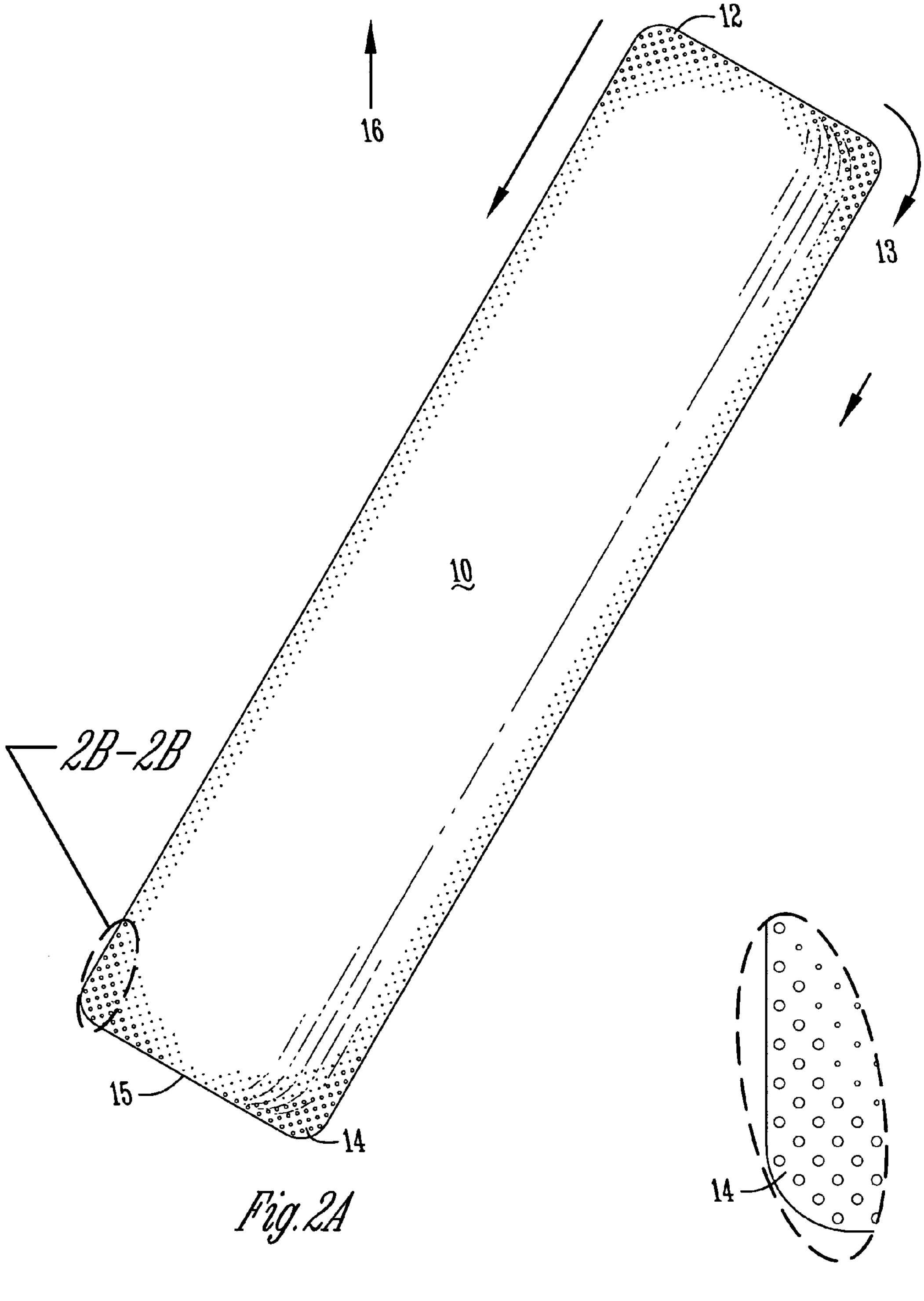


Fig.2A

Fig.2B

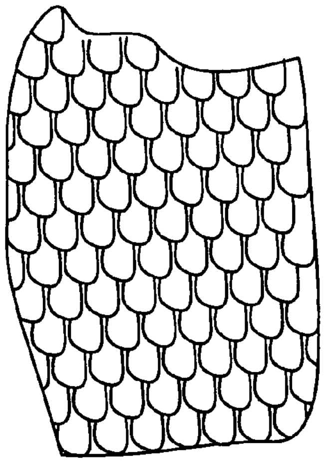


Fig.3C

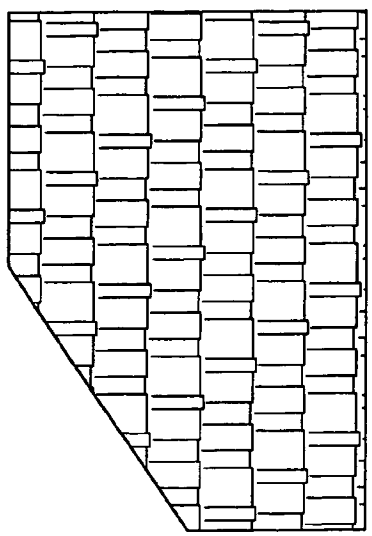


Fig.3B

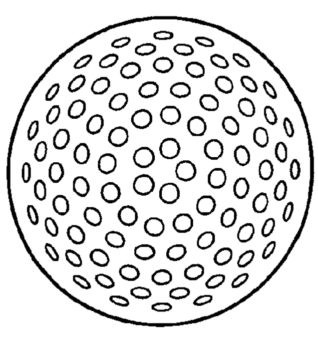


Fig.3A

APPARATUS AND METHOD FOR REDUCING HYDROFOIL CAVITATION

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This non-provisional application claims the benefit of U.S. Provisional Patent Application Ser. No. 60/417,127, filed Oct. 10, 2002, as well as the benefit of U.S. patent application Ser. No. 10/164,730 filed Jun. 6, 2002, the benefit of U.S. patent application Ser. No. 10/171,273 filed Jun. 12, 2002, the benefit of Provisional Application Ser. No. 60/297,314 filed Jun. 12, 2001, the benefit of U.S. Provisional Application Ser. No. 60/361,950 filed Mar. 7, 2002, and the benefit of U.S. patent application Ser. No. 09/718,753 filed on Nov. 22, 2000, now issued as U.S. Pat. No. 6,427,618 for all that they contain and teach.

BACKGROUND OF THE INVENTION

[0002] 1. Field of the Invention

[0003] The present invention relates to rudders (and other underwater hydrofoils) for aquatic vessels and more particularly to a rudder (or any submerged hydrofoil) and methods for minimizing early cavitation. It also has applications for fluid pumps or turbine impellers.

[0004] 2. Problems in the Art

[0005] Rudders provide a vessel with directional stability, control, and maneuverability. Ship rudders are generally vertical hydrofoils with symmetrical profiles. Rudders generate hydrodynamic lift forces to produce ship-turning moments for maneuvering and directional control. The lift force produced varies with the rudder's angle of attack (angle of the rudder relative to the onset flow angle) and the incoming flow velocity (velocity of flow into the rudder). The effectiveness of rudders in performing their hydrodynamic functions is proportional to the square of the incoming flow velocity; thus, rudders are generally placed behind propellers where the incoming flow is accelerated by the rotating propeller. Marine engineers initially determine the overall rudder size (rudder chord, i.e., longitudinal distance from leading edge to trailing edge, and rudder span, i.e., vertical distance from root to tip) based on consideration of the ship's required turning diameter and thus required turning moment.

[0006] These conventional rudders are located either along the ship centerline directly behind the propeller, in the case of a single shaft designs, or behind the propellers and positioned symmetrically about the ship's longitudinal centerline in the case of a multiple shaft designs. Therefore, the rudders are located in the propeller slipstream or trailing wake, i.e., accelerated flow in the propeller wake. The propeller slipstream is a region of highly complex flow having axial, tangential and radial flow components. The rotating propeller accelerates the flow and sheds vortices that impinge on the rudder surface. Consequently, a rudder operating behind a rotating propeller encounters, in addition to the flow at substantially the ship's velocity (ship wake), vortices shed by and induced velocity generated by the propeller (propeller's trailing wake).

[0007] The simple conventional rudder design practice results in problems in terms of rudder performance. Depending on the propeller's size, hydrodynamic loading and position relative to the rudder, the incoming flow to the rudder exhibits induced flow angles (onset flow angles) that can vary longitudinally along the chord of the rudder (chordwise) and vertically along the span of the rudder (spanwise). Because the propeller accelerates and rotates the flow into the rudder and because the vortices shed from the propeller impinge on the rudder surface, the flow entering the rudder plane exhibits larger onset flow angles (angles of incoming flow relative to the ship longitudinal centerline) than would result without the propeller present. As a result of the propeller generating non-zero onset flow angles in the rudder plane, rudders with symmetric profile sections placed parallel to the ship centerline experience non-zero angles of attack, generate hydrodynamic lift, and incur induced drag; even if the ship is operating in a straight ahead course.

[0008] Because of non-zero onset flow angles, suction pressure peaks (highly decreased pressure) occur at or near to the leading edge of the rudder. Surface cavitation can be predicted from the pressure distribution on the rudder surface. Cavitation inception occurs when local pressure drops to or below the local vapor pressure of the flowing fluid. Therefore, in areas of suction pressure peaks, early cavitation inception can occur on the rudder outboard side (on a single propeller).

[0009] Viewing the rudder and propeller from behind the ship, a right-hand rotating (clockwise rotating) propeller will produce flow having velocity components directed to the right of the propeller centerline while left-hand rotating (counterclockwise rotating) propellers will direct components of flow to the left of the propeller centerline. Therefore, depending on the direction of propeller rotation and, thus, the direction of induced flow angle into the rudder, cavitation may occur on either the inboard or outboard side of the rudder in twin shaft designs.

[0010] Early rudder cavitation results in an undesirable compromise in hydrodynamic and acoustic performance of the vessel. Specifically, rudder cavitation induces unsteady hydrodynamic forces, vibration, and rudder erosion. The existence of non-zero onset flow angles also reduces the available rudder angles for avoiding rudder stall at low speeds. Furthermore, the induced drag from the finite lift force as well as the form drag from the rudder cavity creates additional ship resistance, wasting power and degrading performance.

[0011] Ship rudders are subjected to propeller induced velocities and induced flow angles that vary along the rudder span and chord. Because of non-zero onset flow angles, a suction pressure peak is formed at or near the leading edge of the rudder where early cavitation occurs. It would, therefore, be advantageous to both hydrodynamic and acoustic performances to alleviate the occurrence of suction pressure peaks and early cavitation. Thus, there is clearly a need to improve rudder cavitation inception speed (i.e., delay cavitation inception) and to improve hydrodynamic and acoustic performances of rudders.

[0012] Due to the complexity of flow field in the propeller slip-stream, the influence of accelerated cross-flow induced by the propeller onto the rudder was not considered in existing rudder design practice until U.S. Pat. Nos. 5,415,122, 5,456,200 and 6,101,963 by Shen significantly improved the rudder cavitation problem with a "twisted" rudder and rudder tab at the lower end tip.

[0013] For example, on the Arleigh Burke Class destroyers, it had become apparent that rudder cavitation was a serious problem. Unfortunately, this cavity began to form at speeds as low as 23 knots, which means it is present at most normal vessel operating conditions. This cavitation led to erosion of the protective coating on the rudder and led to high maintenance costs for the fleet. To alleviate this phenomenon, Dr. Young T. Shen's rudder design more closely matched the complex flow in the wake of the propeller. By "twisting" the rudder section around the stock, he was able to develop a rudder that would not cavitate under normal loading conditions. In addition, by developing a tip plate for the end of the rudder, he was also able to greatly reduce the tip cavitation from the standard fleet design. For his work, Shen was awarded U.S. patents on both the twisted rudder and tip plate innovations. Models of the twisted rudder were tested in a large cavitation channel and compared to the standard fleet rudder. The twisted rudder showed a significant improvement over the fleet design, not experiencing cavitation until it approached nearly 30 knots.

[0014] If cavitation could be reduced even further by an alternative method, this alternative method would have applications at even higher speeds, such as found on high-speed ferries. At lower speeds, any rudder slightly out of perfect alignment may also experience cavitation, until perfect alignment is achieved. Rudders are often out of perfect straight-ahead alignment. There is a need for minimizing cavitation in waterjet underwater steering plates, for which "twisting" will not correct. Cavitation reduction is even more important in submarine stealth. Submarine rudders are not commonly found in the propeller slipstream; however, minimizing any cavitation in the hydrofoil steering planes is very desirable. There is therefore a need to reduce rudder cavitation even further on any hydrofoil steering system.

FEATURES OF THE INVENTION

[0015] A general feature of the present invention is the provision of a method or methods for maneuvering a surface or submarine ship through water, which overcomes problems found in the prior art.

[0016] A further feature of the present invention is the combination of the twisted rudder (in the slipstream) with the new features provided herein.

[0017] Another feature of the present invention is the combination of the tip plate with the new features provided herein.

[0018] Still another feature of the present invention is the provision of a method (or methods) for reducing rudder cavitation on a straight rudder, twisted rudder or submerged hydrofoil steering plane, with or without tip plates.

[0019] Still yet another feature of the present invention is the provision of a method (or methods) for reducing cavitation on any hydrofoil, including fluid pumps and turbine impellers.

[0020] Another feature of the present invention is the provision of a (rudder/steering plane) cavitation reduction process that incorporates either hydrofoil perforations or surface texture variation individually, or both in combination.

[0021] A further feature of the present invention is the provision of an apparatus that is lighter in weight, yet as strong as the rudder that is replaced.

[0022] A still further feature of the present invention is the provision of a method and apparatus for steering a surface ship or submarine through water that is more efficient at high speed, saving fuel by lowering drag.

[0023] Yet another feature of the present invention is the provision of a method and apparatus for minimizing cavitation damage.

[0024] These, as well as other features and advantages of the present invention will become apparent from the following specifications and claims.

BRIEF SUMMARY OF THE INVENTION

[0025] Rudders are hydrofoils, as are propeller blades. Technology that reduces cavitation in one will reduce cavitation in the other. U.S. patent application Ser. No. 10/164,730 filed Jun. 6, 2002, and U.S. patent application Ser. No. 10/171,273 filed Jun. 12, 2002, by Hilleman, discuss perforated propellers to reduce cavitation for marine propulsion. In the case of a perforated rudder, the same principles apply; it is understood that perforations must not compromise structural strength.

[0026] The less efficient perforated propeller is a trade-off for less cavitation. Increasing propeller pitch also trades efficiency for reduced cavitation; this latter trade-off is well known in the art. Cavitation reduction is advantageous for stealth. In the perforated propeller application, the holes should have smooth rounded edges and should be large enough to avoid biologic blockage, yet be small enough to interfere with efficiency as little as possible. They should be located wherever cavitation is a problem, e.g. ahead of the pitting to avoid cavitation inception. The same may be generally said of the perforated rudder (or any submerged hydrofoil); however, efficiency may be less of a concern, while strength may be more of a concern. A rudder with staggered rounded perforations is nearly as strong as a solid rudder. Any perforation pattern would apply; some examples would be staggered round holes, staggered teardrops, or parallel longitudinal slits running the length of the chord. The longitudinal slits running the length of the chord reduce boundary layer turbulence (as well as cavitation) extremely well. All have the advantage of markedly reducing boundary layer turbulence as well as controlling cavitation on the suction side; they also reduces weight without significantly affecting performance strength.

[0027] The above Hilleman patent applications also discuss surface texture variation to minimize boundary layer drag. Boundary layer drag can be significant in turbulent water; it is a significant cause of submarine cavitation. Frontal wave drag is the primary resistance of surface ships. When both are combined, they essentially comprise the surface ship's drag force in the water while underway. On a well-trimmed rudder, these drag forces act on the rudder; they worsen as rudder alignment worsens. Rudder alignment is not always perfect; therefore, streamlining the rudder surface will help to minimize drag (and decrease cavitation) at all speeds, particularly in turns.

[0028] Surface drag is due to viscous shear forces of the moving water against the surface of the ship and rudder, resulting in eddies and turbulence that cause deceleration, sapping the ship and rudder's momentum.

[0029] The turbulence and eddies increase with increase in passing water speed. Parallel longitudinal ridges, like those found on a phonograph record, would allow the water to flow as close to the surface as possible, without touching it, thereby reducing the turbulence close to the surface. For example, 40 micron phonograph-like ridges covering the greater surface area of the rudder would create a shear-protected layer of similar magnitude, preventing eddies of high-speed fluid from contacting the surface. This would streamline the pressured side of the rudder, reducing drag. A similar texturing resembling fine sharkskin scales or tiny dimples would also have a similar benefit.

[0030] Suction pressure peaks (highly decreased pressure) and associated cavitation often occur at or near to the leading edge of the rudder. Incorporating coarser texturing of larger sized ridges at the rudder's leading edge, that eventually blend into the finer ridges on main body portion of the rudder, helps reduce cavitation on the leading edge's suction side. The coarser ridges act like golf ball dimples to draw pressurized water closer to the low-pressure surface, much as golf ball dimples pressurize the air behind the golf ball. There are differences, since air is compressible; however, the fluid principles are similar. Drag on a golf ball comes mainly from air-pressure forces. The drag arises when the pressure in front of the ball is significantly higher than the pressure behind the ball. The only practical way of reducing this differential is to design the ball so that the main stream of air flowing by it is as close to the surface as possible.

[0031] The dimples augment the turbulence very close to the surface, bringing the high-speed air stream closer, causing it to travel further around the ball before separating and "tucking it in" behind the round ball to a much greater degree. Reducing the "low pressure wake" generated thus increases the pressure behind the ball, which reduces the pressure differential, as well as it reduces the vacuum magnitude, and therefore results in an overall drag reduction. This drag reduction allows the dimpled golf ball to fly about two and one half times farther than an identical but undimpled ball. The faster the undimpled ball moves, the more the drag is increased; however speed does not affect drag very much on a ball with dimples.

[0032] Water, being incompressible, has suction turbulence rather than a vacuum pressure; suction turbulence fosters cavitation. Minimizing suction turbulence, by variable texturing (coarser ridges or golf-ball dimples) on the rudder's leading edge, will minimize cavitation on the rudder's leading edge. In addition to coarser ridges and golf-ball dimples, other textures, such as large fish scale patterns may be used to accomplish the same effect. Mammal-like (Cetacea) polymer coatings or fluid-backed rubber coatings could also be utilized in a similar variable role on the leading edge (as well as on the main body).

[0033] Suction turbulence is present at the trailing edge. The trailing edge is often rounded to minimize cavitation, as a sharp trailing edge can lead to cavitation at lower speeds. The golf-ball dimple effect, the coarser longitudinal ridges, or the larger fish scale texturing would be of great advantage in this location, as they would pressurize the rounded trailing edge. In addition, the golf ball dimpling effect could be incorporated in Dr. Shen's tip plate design, for example, dimpling the rounded rudder tab at the lower end tip would pressurize a greater portion of it's rounded trailing end.

BRIEF DESCRIPTION OF THE DRAWINGS

[0034] **FIG. 1** is a pictorial side view with evenly spaced round perforations throughout the body of the rudder.

[0035] **FIG. 2** is a pictorial bottom (or top) view of the rudder illustrating a golf-ball dimple pattern on the rounded corners and edges.

[0036] **FIG. 3** is a pictorial view of some of the different surface textures that could be used in the variable rudder texturing.

DETAILED DESCRIPTION OF THE INVENTION

[0037] The present invention will be described as it applies to its preferred embodiment. It is not intended that the present invention be limited to the described embodiment. It is intended that the invention cover all modifications and alternatives, which may be included within the spirit and scope of the invention.

[0038] Referring to **FIG. 1**, **FIG. 1A** describes an embodiment in which the entire rudder **10** is covered by alternating round-hole perforations **11**, as magnified in **1**B. The technique of drilling holes is well known in the art. In this case the rounded perforations would result in a dimpled surface (**FIG. 3A**), capable of evenly pressurizing the suction side as well as augmenting surface turbulence and reducing boundary layer drag on the pressure side (from water passage through the holes).

[0039] In the **FIG. 2** bottom rudder view, this embodiment illustrates surface texture minimizing leading edge cavitation and trailing edge cavitation, without perforations. Rudder **10** has a leading edge **12** and a trailing edge **14**, moving in the direction of arrow **16**. **FIGS. 2A and 2B** illustrate golf ball dimple pattern on the rounded leading and trailing edges. Because they cover all rounded edges, they always cause the water to flow more around and behind the rounded dimpled surface more than that seen on a smooth rounded surface. This reduces the area and intensity of suction turbulence, which in turn reduces cavitation on the leading edge suction-prone area **13** and trailing edge suction-prone area **15**.

[0040] **FIG. 3A** better illustrates the golf ball dimple surface texture treatment shown in **FIG. 2**. If it were to be used on a non-perforated rudder, the dimples **11** on the main body of rudder **10** would be much smaller than the heavy pronounced dimples in the rounded leading **12** and trailing edges **14**. These small dimples would more closely approximate the size of the longitudinal phonograph ridges previously mentioned. The longitudinal ridges could be used in another embodiment, as could the shingle pattern of **3**B or the shark or fish scale pattern of **3**C. These patterns could be impressed in the rubber coating during molding. In each case, smaller texturing is used to reduce drag on the pressure side of the rudder **10** main body, and coarser texturing is utilized on the curved surfaces to augment surface turbulence and carry water pressure around the curve, pressurizing the back side (**13&15**) more.

[0041] Maximum benefit is possible through a combination of perforations and variable texturing. Combining **FIG.**

1 and **FIG. 2** would be an example of such an embodiment. The combination of perforations could be utilized on any submerged hydrofoil to reduce cavitation, regardless of whether it is a propeller, pump impeller, turbine impeller, waterjet steering plate, lifting hydrofoil or submarine steering plane. It is to be further understood that the hydrofoil system is dynamically designed according to desired performance characteristics.

[**0042**] This is therefore believed to have accomplished all of the stated objectives of the invention including the provision of a method or methods for maneuvering a surface or submarine ship through water, which overcomes problems found in the prior art; the combination of the twisted rudder (in the slipstream) with the new features provided herein; the combination of the tip plate with the new features provided herein; the provision of a method (or methods) for reducing rudder cavitation on a straight rudder, twisted rudder or submerged hydrofoil steering plane, with or without tip plates; the provision of a method (or methods) for reducing cavitation on any hydrofoil; the provision of a (rudder/steering plane) cavitation reduction process that incorporates either hydrofoil perforations or surface texture variation individually, or both in combination; the provision of an apparatus that is lighter in weight yet as strong as the rudder that is replaced; the provision of a method and apparatus for steering a surface ship or submarine through water that is more efficient at high speed, saving fuel by lowering drag; and the provision of a method for minimizing cavitation damage. Accordingly, all such modifications and additions are deemed to be within the scope of the invention, which is to be limited only by the following claims.

1. A method of reducing hydrofoil cavitation on a ship, the method comprising:

providing perforations in a hydrofoil, the hydrofoil having a leading edge, a trailing edge, a suction side and a pressure side, the perforations providing a passage for water from the suction side to the pressure side, and

maneuvering the ship through water.

2. A hydrofoil that reduces cavitation, the hydrofoil comprising:

a main body entirely covered by alternating round-hole perforations capable of evenly pressurizing a suction side as well as augmenting surface turbulence and reducing boundary layer drag on a pressure side;

a trailing edge on the main body; and

a surface texturing on the trailing edge.

3. The hydrofoil of claim 2 further comprising a leading edge on the main body and surface texturing on the leading edge.

4. The hydrofoil of claim 2 wherein the surface texturing comprises dimples.

5. The hydrofoil of claim 2 wherein the surface texturing comprises longitudinal grooves.

6. The hydrofoil of claim 2 wherein the surface texturing comprises scales.

7. The hydrofoil of claim 2 wherein the surface texturing comprises shingles.

8. A hydrofoil that reduces cavitation, the hydrofoil comprising:

a main body having a leading edge, a trailing edge, a suction side and a pressure side; and

perforations in the main body providing a passage for water from the suction side to the pressure side.

* * * * *