Title: Vessel for operating on a body of water, comprising an aft foil configured for lowering a total resistance of the vessel

FIELD OF THE INVENTION

The present invention relates to a vessel for operating on a body of water (W) comprising:

- a hull, having a mirror plane (S), designed for non-planing operation on the water body, during operation displaying a waterline (WL) and having a forward direction (X) in a horizontal plane (HP) with a forward hull portion, an aft hull portion, and a central hull portion, the hull being configured to have the aft hull portion with a smaller water displacement relative to a water displacement of the central hull portion; and
- an aft foil affixed to the aft hull portion with two or more connecting members, configured to be below the waterline (WL) during operation, spaced from the hull, and suitable for generating a lift force (L_{af}), wherein the aft foil is affixed to the aft hull portion in such a way, that during operation a free fluid surface (FFS) is present above the aft foil.

BACKGROUND OF THE INVENTION

International patent publications WO 2004020276 A1, WO 2007148966 A2 and/or WO 2016010423 A1 by the present applicant disclose vessels with a stationary aft foil oriented horizontally below the hull of a vessel. The respective aft foil uses energy that is present in the flow for developing thrust. At the location where the aft foil is fitted to ships (near the stern of the vessel) the flow is inclined aft and upwards. When the aft foil is positioned in this flow a lift force is developed at right angles thereto such that the horizontal component thereof constitutes a thrust force.

KR 2006 0072847 A discloses a barge with a hydrofoil.

EP 0290 170 A2 discloses a vessel with a foil to generate a downward force in the flow positioned below the stern.

JP H11 180379 A discloses a vessel with a stern backwash reduction device.

EP 3 885 245 A1 discloses a vessel for floating in a body of water, comprising a hull having an aft hull section and an aft body arranged at a distance from the aft hull section, thereby forming a passage into which water can flow. The aft body and the aft hull section are designed to minimize the vessel's stern wave during forward movements.

However, the abovementioned patent publications focus on optimizing the thrust force provided by the aft foil, not on improving the lift-over-drag ratio (L/D) of the aft foil, let alone on decreasing the total resistance generated by the vessel as a whole, i.e. the total resistance generated by the hull, connecting members and the aft foil (and any other resistance-generating bodies present on the vessel).

An object of the present invention is thus to provide an aforementioned vessel with an aft foil for generating a lift force, wherein L/D of the aft foil is optimized and, in a broader sense, wherein the resistance of the vessel as a whole is further optimized.

Further objects of the invention are to provide an aforementioned vessel, wherein wave energy otherwise lost in the vessel’s wake can be regained, to provide an aforementioned vessel, wherein the wave height in the vessel’s wake is reduced, and to provide an aforementioned vessel, wherein pitch, heave and roll behaviour is improved. Yet a further object of the invention is to provide an aforementioned vessel, wherein flow separation from either the aft foil or the hull is prevented or at least postponed. Yet an even further object of the invention is to improve the running trim of the vessel.

SUMMARY OF THE INVENTION

Hereto, according to the invention, a vessel for operating on a body of water (W) is provided, comprising:

- a hull, having a mirror plane (S), designed for non-planing operation on the water body, during operation displaying a waterline (WL) and having a forward direction (X) in a horizontal plane (HP) with a forward portion, an aft portion, having a buttock angle (β), and a central portion, the hull being configured to have the aft portion with a smaller water displacement relative to a water displacement of the central portion; and

- an aft foil affixed to the aft hull portion with two or more connecting members, configured to be below the waterline during operation, spaced from the hull, and suitable for generating a lift force (L_{af}), wherein a span (b_{af}) of the aft foil is at most 0.95 times a beam overall (BOA) of the vessel, the aft foil comprising a symmetric or asymmetric hydrofoil section, having positive camber, a lift coefficient ($C_{L,\ af}$) and a zero lift angle (α_0), as well as a chord (c_{af}) having a chord length ($L_{c,\ af}$), wherein the aft foil is affixed to the aft hull portion in such a way, that during operation a free fluid surface (FFS) is present above the aft foil,

wherein the chord of the aft foil is configured to have a geometric angle (α_g) with respect to the horizontal plane (HP) equal to $180 / (2\pi^2) * l * C_{L,\ af} + \alpha_0 - k * \beta$, wherein k represents a factor taking into account the flattening of the flow below the aft portion at increasing distance from the aft portion, being between 0 and 1.25, and l represents a factor to compensate for the fact that the aft foil in practice is a three-dimensional object and not a two-dimensional one, being between 0 and 1.25. Preferably, k is between 0.5 and 1.0 and l is between 0.4 and 0.9, such as between 0.5 and 0.8.

Due to the provision of a vessel with the aforementioned features, the aft foil is allowed to achieve optimal lift-to-drag ratios. Furthermore, the resistance of the vessel as a whole is reduced. Moreover, pitch, heave and roll behaviour is improved. Additionally, the wave height in the vessel's wake is reduced and energy otherwise lost in the vessel's wake is regained. Furthermore, the running trim of the vessel is improved. Therein, the Applicant has found that the buttock angle of the vessel has a significant influence on the performance of the aft foil - the Applicant advantageously has found a way to take the buttock angle into account when determining the optimal geometric angle (α_g) with respect to the horizontal plane to achieve optimal aft foil performance. This is not known from the prior art.

An aft foil with the abovementioned characteristics allows for constantly obtaining the best lift-to-drag ratio from the aft foil.

In the context of the present application "geometric angle" or "angle of incidence" (α_g) refers to an angle of a chord of a (respective) foil with respect to the horizontal plane. The expression "angle of attack" (α) is to be interpreted as being the angle between the incoming flow and the chord of the (respective) foil. Furthermore, "free fluid surface" refers to the water surface that is in contact with air. The symbol "k" represents a factor taking into account the "flattening" of the flow below the aft

portion at increasing distance from the aft portion (wherein $\alpha = \alpha_g + k * \beta$). The value of k may exceed 1.0 to account e.g. for the upcoming flow of water aft of the transom. The symbol/letter “l” represents a factor to compensate for the fact that the aft foil in practice is a three-dimensional object and not a two-dimensional one, leading to different flow characteristics (the skilled person will know that the lift curve slope of a three-dimensional foil is always less than that of the foil sections it features). The value of l may also exceed 1.0, to account for effects of e.g. the propeller, which will increase the lift coefficient. The span b_{af} means the distance (transversal to the mirror plane (S)) between one aft foil end and another aft foil end. Therein, the aft foil may be divided in aft foil parts, as will be explained later. For calculating the span b_{af}, aft foil “end” in this respect means that outside of the aft foil end no further aft foil parts are present. Furthermore, “non-planing” in the context of the present application means having a Froude number based on waterline length lower than approximately 1.0.

It should furthermore be noted that all angles mentioned in the present patent application are expressed in degrees. In case of a vessel with a buttock angle (β) varying along the stern of the vessel (i.e. transversal to the mirror plane (S)), β indicates the average buttock angle.

An embodiment relates to an aforementioned vessel, wherein the water body displays a water surface (WS) during operation, wherein the free fluid surface (FFS) area is equal to at least 50%, preferably at least 75%, such as 100% of a vertically projected surface area (VPSA) of the aft foil on the water surface, i.e. when the aft foil is vertically projected on the water surface in an “unhindered” manner - not obstructed by other parts of the vessel. Thus, pressure reflection phenomena caused by the foil on the hull are thereby mitigated as much as possible.

An embodiment relates to an aforementioned vessel, wherein the aft foil is arranged at a vertical distance below an extrapolated buttock angle line of at most 0.25 * the chord length ($L_{c,\ af}$) of the aft foil, which further improves the performance of the aft foil in view of the incoming flow below the stern/hull of the vessel. “Extrapolated buttock angle line” herein refers to a (fictional) line drawn to represent the (average) buttock angle (β) of the vessel (in side view), extending in a backward direction past the actual confines of the vessel.

An embodiment relates to an aforementioned vessel, wherein the aft foil is configured to have a lift coefficient ($C_{L,\ af}$) of 0 to 1, such as 0.2 to 0.7. Such a

lift coefficient further optimizes the lift-to-drag ratio of the aft foil and reduces total vessel resistance.

An embodiment relates to an aforementioned vessel, wherein, during operation, the aft foil is configured to have an angle of attack (α) of -5 to 8 degrees with respect to an incoming flow (IF). Thus, the aft foil is able to provide the required lift, as well as an optimal lift-to-drag ratio, for a wide range of inflow directions below the hull.

An embodiment relates to an aforementioned vessel, wherein, during operation, the aft foil is configured to have an angle of attack (α) of -2 to 5 degrees with respect to an incoming flow (IF), to even further optimize the lift-to-drag ratio of the aft foil, while preventing flow separation as much as possible.

An embodiment relates to an aforementioned vessel, wherein, during operation, the aft foil is configured to have an angle of attack (α) of -2 to 2 degrees with respect to an incoming flow (IF), yet even further optimizing the lift-to-drag ratio of the aft foil and yet even further decreasing chances of the flow separating from the aft foil.

An embodiment relates to an aforementioned vessel, wherein an aspect ratio (AR_{af}) of the aft foil is 2 to 30. Thus, an optimal balance may be achieved between hydrodynamic performance of the aft foil on the one hand and structural requirements on the other hand.

An embodiment relates to an aforementioned vessel, wherein an aspect ratio (AR_{af}) of the aft foil is 5 to 15, for instance 6 to 7, to even further optimize the aforementioned balance between performance on the one hand and structural requirements on the other hand.

An embodiment relates to an aforementioned vessel, wherein an aspect ratio (AR_{af}) of the aft foil is 7 to 10, in practice leading to the most optimal hydrodynamic efficiency of the aft foil, at the same time decreasing the total resistance of the vessel.

An embodiment relates to an aforementioned vessel, wherein the span (b_{af}) of the aft foil is 0.3 to 0.95 of a beam overall (BOA) of the vessel. Thus, the aft foil comprises sufficient “span” to generate the required lift force, having little effect on other performance characteristics of the vessel, such as maneuverability.

An embodiment relates to an aforementioned vessel, wherein the span (b_{af}) of the aft foil is 0.4 to 0.95 of a beam overall (BOA) of the vessel, to even

further optimize the balance between the required lift force on the one hand and performance characteristics of the vessel on the other hand.

An embodiment relates to an aforementioned vessel, wherein the span (b_{af}) of the aft foil is 0.5 to 0.95 of a beam overall (BOA) of the vessel. In practice, the most optimal balance between the required lift force on the one hand and performance characteristics of the vessel on the other hand is thus achieved.

An embodiment relates to an aforementioned vessel, wherein the aft foil is affixed to the aft hull portion with two or more connecting members comprising two or more struts, wherein each of the two or more struts is affixed to the aft hull portion at a first position, such as an innermost location, and wherein each of the two or more struts is connected to the aft foil at a second position, such as an outermost location.

An embodiment relates to an aforementioned vessel, wherein the aft foil is affixed to the aft hull portion with two, three, four, five, six or seven struts, depending on design and structural requirements.

An embodiment relates to an aforementioned vessel, wherein each of the two or more struts has a chord length ($L_{c,\ strut}$) that varies from the first position towards the second position. Thus, the hydrodynamic characteristics of the two or more struts can be optimized in order to further improve the overall hydrodynamic performance of the aft foil system and the vessel as a whole.

An embodiment relates to an aforementioned vessel, wherein each of the two or more struts is tapered from the first position towards the second position to further improve the hydrodynamic and structural efficiency of the two or more struts.

An embodiment relates to an aforementioned vessel, wherein a taper ratio of each of the two or more struts from the first position towards the second position is 0.5 to 2, preferably 0.7 to 1.5, more preferably 0.8 to 1.1. In practice, optimal hydrodynamic and structural performance of the two or more struts can thus be achieved.

An embodiment relates to an aforementioned vessel, wherein the aft foil comprises a nacelle at the second position where each of the two or more struts connects to the aft foil. Thus, aft foil resistance is even further reduced and L/D is further optimized and flow separation is prevented.

An embodiment relates to an aforementioned vessel, wherein the nacelle is provided with one or more upwardly extending and/or downwardly extending

winglets. The induced drag of the one or more nacelles is thus reduced and again L/D of the aft foil system as a whole improves.

An embodiment relates to an aforementioned vessel, wherein each of the two or more struts and/or the aft foil comprises one or more vortex generators and/or interceptors. In practice, this greatly reduces the probability of flow separation occurring at the two or more struts and/or the aft foil.

An embodiment relates to an aforementioned vessel, wherein the one or more vortex generators and/or interceptors are arranged near the second position. The Applicant has found that the second position is the most sensitive to flow separation phenomena and the largest gains are thus to be achieved when the one or more vortex generators and/or interceptors are arranged at or near the second position.

An embodiment relates to an aforementioned vessel, wherein the two or more struts are provided with one or more anti-ventilation plates, wherein each of the two or more struts may for instance comprise one, two, three, four or five anti-ventilation plates. Thus, surface air is prevented from being transported to undesirable locations at the negative pressure side of the aft foil and/or the two or more struts.

An embodiment relates to an aforementioned vessel, wherein the aft foil comprises two side aft foil parts situated on opposing sides of the mirror plane (S), in a direction transversal to the mirror plane (S). The two side aft foil parts may be separated from each other or connected to each other. Thus, the aft foil may be tuned to specific design requirements of the vessel, for instance in view of the design of the propulsion system.

An embodiment relates to an aforementioned vessel, wherein the aft foil comprises a central aft foil part situated at the mirror plane (S), wherein the two side aft foil parts are situated on opposing sides of the central aft foil part, wherein the two side aft foil parts are connected by the central aft foil part. Thus, even further “tuning” of the aft foil system can be achieved, both in view of design requirements, as well as in view of hydrodynamic performance. The central aft foil part may for instance be adapted to flow characteristics of a central portion of the wake, whereas the side aft foil portions may be tuned to side portions of the vessel’s wake. Or the aft foil system may be tuned to the characteristics of the specific propulsion system used on the vessel.

An embodiment relates to an aforementioned vessel, wherein the central aft foil part has a central aft foil part chord length ($L_{c,\ central}$) and the two side aft foil parts have a side aft foil part chord length ($L_{c,\ side}$), being different from the central aft foil part chord length. As mentioned in the foregoing, a further optimized aft foil design may thus be realized, even further improving the aft foil performance and the vessel's overall resistance.

An embodiment relates to an aforementioned vessel, wherein the central aft foil part chord length ($L_{c,\ central}$) is 60 to 90%, preferably around 75% of the side aft foil part chord length ($L_{c,\ side}$). The central aft foil part is thus "shorter" than the side aft foil parts and as a consequence has a higher aspect ratio, further improving the hydrodynamic efficiency of the aft foil.

An embodiment relates to an aforementioned vessel, wherein the central aft foil part chord length ($L_{c,\ central}$) is 30 to 40%, preferably around 35% of the side aft foil part chord length ($L_{c,\ side}$). In practice, such a ratio achieves an even better hydrodynamic performance of the aft foil.

An embodiment relates to an aforementioned vessel, wherein the central aft foil part chord length ($L_{c,\ central}$) is 5 to 15%, preferably around 10% of the side aft foil part chord length ($L_{c,\ side}$). In practice, this ratio achieves the best hydrodynamic performance of the aft foil, whereas at the same time structural requirements can still be met.

An embodiment relates to an aforementioned vessel, wherein one or more outer ends of the aft foil, in a direction transversal to the mirror plane (S), comprise one or more upwardly extending and/or downwardly extending winglets. Thus, induced drag of the aft foil is further decreased.

An embodiment relates to an aforementioned vessel, wherein the aft foil has a quarter chord sweep angle (Λ) of -30 to 30 degrees, preferably -15 to 15 degrees, more preferably -5 to 5 degrees, allowing for a further drag reduction of the aft foil, improved L/D and improved performance, particularly at higher vessel speeds.

An embodiment relates to an aforementioned vessel, wherein a maximum camber of the aft foil is 0.05 times, preferably 0.03 times, more preferably 0.01 times, the chord length ($L_{c,\ af}$) of the asymmetric hydrofoil section, leading to substantial lift increases at lower angles of attack.

Another aspect of the invention concerns a computer-implemented method of designing an aforementioned vessel, comprising:

- providing a reference vessel (V_{ref}) with a hull having a reference waterline length (LWL_{ref}) and a reference displacement (D_{ref});
- increasing the reference waterline length (LWL_{ref}) at the aft hull portion, by 1 to 15%, preferably by 1 to 10%, more preferably by 1 to 5 %, most preferably by 1 to 3%, such as around 2%, of the reference waterline length (LWL_{ref}), giving a hull with a design waterline length (LWL_{des});
- reducing the reference displacement (D_{ref}) of the hull of the vessel by removing volume at the aft hull portion of the reference vessel, by 0.25 to 3%, preferably by 0.25 to 1.5%, more preferably by 0.25 to 0.75%, most preferably around 0.5%, of the reference displacement (D_{ref}), giving a design displacement (D_{des});
- designing the aft foil to be affixed to the aft hull portion with two or more connecting members, configured to be below the waterline (WL) during operation, spaced from the hull, and suitable for generating a lift force (L_{af}), wherein a span (b_{af}) of the aft foil (6) is at most 0.95 times a beam overall (BOA) of the vessel, the aft foil comprising a symmetric or asymmetric hydrofoil section, having positive camber, a lift coefficient ($C_{L,\,af}$) and a zero lift angle (α_0), as well as a chord (c_{af}) having a chord length ($L_{c,\,af}$),

wherein the aft foil is affixed to the aft hull portion in such a way, that, during operation, a free fluid surface (FFS) is present above the aft foil, and

wherein the chord of the aft foil is configured to have a geometric angle (α_g) with respect to the horizontal plane (HP) equal to $180 / (2\pi^2) * l * C_{L,\,af} + \alpha_0 - k * \beta$, wherein k represents a factor taking into account the flattening of the flow below the aft portion at increasing distance from the aft portion, being between 0 and 1.25, and l represents a factor to compensate for the fact that the aft foil in practice is a three-dimensional object and not a two-dimensional one, being between 0 and 1.25. The Applicant has found that the above design of the aft hull portion leads to greatly improved performance of the aft foil and a significant reduction of total vessel resistance.

An embodiment relates to an aforementioned method of producing an aforementioned vessel, comprising the steps of:

- providing a hull, having a mirror plane (S), designed for non-planing operation on the water body (W), during operation displaying a waterline (WL) and having a forward direction (X) in a horizontal plane with a forward hull portion, an aft hull portion, having a buttock angle (β), and a central hull portion, the hull being

configured to have the aft hull portion with a smaller water displacement relative to a water displacement of the central hull portion; and

- affixing the aft foil to the aft hull portion with two or more connecting members, configured to be below the waterline during operation, spaced from the hull, and suitable for generating a lift force (L_{af}), wherein a span (b_{af}) of the aft foil (6) is at most 0.95 times a beam overall (BOA) of the vessel, the aft foil comprising a symmetric or asymmetric hydrofoil section, having positive camber, a lift coefficient ($C_{L,\,af}$) and a zero lift angle (α_0), as well as a chord (c_{af}) having a chord length ($Lc_{,\,af}$),

wherein the aft foil is affixed to the aft hull portion in such a way, that, during operation, a free fluid surface (FFS) is present above the aft foil, and

wherein the chord of the aft foil is configured to have a geometric angle (α_g) with respect to the horizontal plane (HP) equal to $180 / (2\pi^2) * l * C_{L,\,af} + \alpha_0 - k * \beta$, wherein k represents a factor taking into account the flattening of the flow below the aft portion at increasing distance from the aft portion, being between 0 and 1.25, and l represents a factor to compensate for the fact that the aft foil in practice is a three-dimensional object and not a two-dimensional one, being between 0 and 1.25.

An embodiment relates to an aforementioned method of producing an aforementioned vessel, comprising the further steps of:

- designing the vessel using the aforementioned computer-implemented method; and
- providing, such as producing, the hull with the design waterline length (LWL_{des}) and the design displacement (D_{des}).

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will be explained hereafter with reference to exemplary embodiments of a vessel and methods according to the invention and with reference to the drawings. Therein:

Figure 1 shows a schematic view of an exemplary embodiment of a vessel with an aft foil according to the invention;

Figure 2 shows a close-up schematic view of an exemplary embodiment of a vessel with an aft foil according to the invention;

Figure 3 shows a schematic perspective view of an exemplary embodiment of a vessel with an aft foil according to the invention, wherein the aft foil is connected to the aft portion with three struts;

Figure 4 shows a schematic perspective view of an exemplary embodiment of a vessel with an aft foil according to the invention, wherein the aft foil comprises two nacelles and is connected to the aft portion with two struts;

Figure 5 shows a schematic perspective view of an exemplary embodiment of a vessel with an aft foil according to the invention, wherein the aft foil is connected to the aft portion with four struts, wherein two struts provided with anti-ventilation plates;

Figure 6 shows a schematic perspective view of an exemplary embodiment of an aft foil according to the invention, wherein the aft foil is shown with a strut for connection to the aft portion of the hull, as well as vortex generators and a Gurney flap;

Figure 7 shows a schematic perspective view of an exemplary embodiment of a vessel with an aft foil according to the invention, wherein the aft foil is connected to the aft portion with three struts, wherein two struts have a variable chord length;

Figure 8 shows a schematic perspective view of an exemplary embodiment of a vessel with an aft foil according to the invention comprising two separate side aft foil parts;

Figure 9 shows a schematic perspective view of an exemplary embodiment of an aft foil according to the invention comprising a central aft foil part situated at the mirror plane (S) and two side aft foil parts; and

Figure 10 shows a schematic perspective view of another exemplary embodiment of a vessel with an aft foil according to the invention comprising a central aft foil part situated at the mirror plane (S) and two side aft foil parts.

DETAILED DESCRIPTION

As mentioned in the foregoing, Figure 1 shows a schematic view of an exemplary embodiment of a vessel 1 with an aft foil 6 according to the invention. Figure 2 shows a close-up schematic view of an exemplary embodiment of a vessel 1 with an aft foil 6 according to the invention. The vessel 1 may have a length of 5 to

300 m, for example 5 to 200 m, for instance 10 to 60 m, such as 20 to 30 m. Figure 1 more specifically shows a vessel 1, such as a sailing yacht or boat or a motor-driven vessel. The vessel 1 is configured for operation on a body of water W, such as a sea, a lake or an ocean. The vessel 1 comprises a hull 2, having a mirror plane S (i.e. extending in a longitudinal/forward direction X), designed for non-planing operation on the water body W. During operation the hull 2 displays a waterline WL and has a forward direction X in a horizontal plane HP with a forward hull portion 3, an aft hull portion 5, and a central hull portion 4. The hull 2 is configured such that the aft hull portion 5 has a smaller water displacement relative to a water displacement of the central portion 4. An aft foil 6 is affixed to the aft hull portion 5, such as the transom, with two or more connecting members 7. The aft foil 6 is configured to be below the waterline WL during operation. The aft foil 6 is spaced from the hull 2 and is suitable for generating a lift force L_{af} (as shown in Figure 2). The aft foil 6 is affixed to the aft hull portion 5 in such a way, that during operation a free fluid surface FFS is present above the aft foil 6 (see Figure 2). A recess may be present above the aft foil 6 to prevent pressure reflection phenomena.

A span b_{af} of the aft foil 6 (please refer to Figure 3) is at most 0.95 times a beam overall (BOA) of the vessel 1, such as 0.8 to 0.95. As shown in Figure 2, the aft foil 6 comprises an asymmetric hydrofoil section, having positive camber, a lift coefficient $C_{L,\,af}$ and a zero lift angle α_0, as well as a chord c_{af} having a chord length $Lc_{,\,af}$. A symmetric hydrofoil section is also conceivable.

As shown in Figure 2, according to the invention, the aft foil 6 is configured to have a geometric angle α_g with respect to the horizontal plane HP equal to $180 / (2\pi^2) * l * C_{L,\,af} + \alpha_0 - k * \beta$, wherein k represents a factor taking into account the flattening of the flow below the aft portion at increasing distance from the aft portion, being between 0 and 1.25, and l represents a factor to compensate for the fact that the aft foil in practice is a three-dimensional object and not a two-dimensional one, being between 0 and 1.25. The symbol/letter “k” represents a factor taking into account the “flattening” of the incoming flow IF below the aft portion at increasing distance from the aft portion 5. The symbol β represents the buttock angle of the aft portion 5, wherein β may be 0 - 30 degrees, such as 0 - 25 degrees, such as 0 - 20 degrees, such as 0 - 15 degrees, for instance 0 - 5 degrees (i.e. horizontal to moderate buttocks), 5 - 10 degrees (i.e. moderate to steep buttocks) or 10 - 15 degrees (i.e. steep to extreme buttocks) (wherein $\alpha = \alpha_g + k * \beta$). The symbol/letter “l” represents a

factor to compensate for the fact that the aft foil 6 in practice is a three-dimensional object and not a two-dimensional one, as the skilled person will understand. All angles are in degrees.

The aft foil 6 may be configured to have a lift coefficient $C_{L,\ af}$ of 0 to 1.0 to optimize L/D and the total resistance of the vessel 1. Preferably, the aft foil 6 is configured to have a lift coefficient $C_{L,\ af}$ of 0.2 to 0.7. Preferably, the non-planing vessel 1 according to the invention operates in a (relatively low) speed regime corresponding to a Froude number of lower than 0.5, such as lower than 0.4.

The aft foil 6 has a leading edge 20 and a trailing edge 21, as more clearly shown in Figure 2. As mentioned in the foregoing, the hull 2 has a forward direction X in a horizontal plane HP, i.e. during operation the horizontal plane HP will usually be aligned with the forward direction X of the vessel 1 and the waterline WL. The connection members 7 may connect to the aft foil 6 at the centre of pressure, i.e. approximately at a distance of ¼ $L_{c,\ af}$ from the leading edge 20 of the aft foil 6. In some embodiments, the leading edge 20 and trailing edge 21 may furthermore have a convex, respectively, concave, shape. The leading edge 20 and trailing 21 may furthermore run parallel to each other, providing the aft foil 6 with an arrow or boomerang shape (with backward sweep), when viewed from above. During operation, when the vessel 1 is moving in the forward direction X, a flow is generated below the hull 2. The incoming flow IF upstream of the aft foil 6, below the hull 2, has a certain angle of attack α with respect to the chord of the aft foil c_{af}. The chord length of the aft foil $L_{c,\ af}$ may be 0.3 to 5 m, such as 0.5 to 2 m. However, this highly depends on the specific requirements of the vessel 1 at hand.

As shown in Figures 1 and 2, the water body W displays a water surface WS during operation. Preferably, the free fluid surface FFS area is equal to at least 50%, preferably at least 75%, such as 100% of a vertically projected surface area VPSA of the aft foil 6 on the water surface WS, as shown in Figure 2, i.e. the vertically projected surface area VPSA is “unobstructed” by bodies attached to the vessel 1 or the vessel 1 itself. As shown in Figures 1 and 2, and as mentioned before, the aft hull portion 6 may be provided with a recess near the transom for creating the free fluid surface FFS. Although Figure 2 shows a propeller of a propulsion system, the skilled person will understand that many more types or propulsion systems are conceivable.

Referring to Figure 2, during operation, the aft foil 6 is preferably configured to have an angle of attack α of -5 to 8 degrees with respect to an incoming

flow IF. The aft foil 6 is more preferably configured to have an angle of attack α of -2 to 5 degrees with respect to an incoming flow IF. Even more preferably, the aft foil 6 is configured to have an angle of attack α of -2 to 2 degrees with respect to an incoming flow IF.

Preferably, an aspect ratio AR_{af} of the aft foil 6 is 2 to 30. More preferably, an aspect ratio AR_{af} of the aft foil 6 is 5 to 15. Even more preferably, an aspect ratio AR_{af} of the aft foil 6 is 7 to 10.

As shown in Figure 3, the span b_{af} of the aft foil 6 may be 0.3 to 0.795 of a beam overall (BOA) of the vessel 1. More preferably, the span b_{af} of the aft foil 6 is 0.4 to 0.95 of a beam overall (BOA) of the vessel 1. Even more preferably, the span b_{af} of the aft foil 6 is 0.5 to 0.95 of a beam overall (BOA) of the vessel 1.

As shown in Figure 3, the aft foil 6 may be affixed to the aft hull portion 5 with two or more connection members 7 in the form of struts 8, wherein the two or more struts 8 are affixed to the aft hull portion 5 at a first position 9 and wherein the two or more struts 8 are connected to the aft foil at a second position 10. The aft foil 6 may be affixed to the aft hull portion 5 with one, two, three, four, five, six or seven struts 8. Figure 3 shows the presence of three struts 8. The two or more struts 8 may have a chord length $L_{c,\ strut}$ that varies from the first position 9 towards the second position 10. The two or more struts 8 may furthermore be tapered from the first position 9 towards the second position 10. A taper ratio of the two or more struts 8 from the first position 9 towards the second position 10 is 0.5 to 2, preferably 0.7 to 1.5, more preferably 0.8 to 1.1. Please note that the first position 9 and the second position 10 are indicated only with respect to one strut, for sake of clarity. The aft foil 6 itself may also be tapered, for instance having a taper ratio of 0.5 to 1.2.

The aft foil 6 may also have various shapes, such as a curved (“boomerang”) shape. The aft foil 6 may be curved in the horizontal plane HP or in a plane transversal to the mirror plane S and the horizontal plane HP.

As shown in Figures 4, 9 and 10, the aft foil 6 may comprise a nacelle 11 at the second position 10 where the two or more struts 8 connect to the aft foil 6. The nacelles 11 may protrude upstream of the leading edge 20 of the aft foil by for instance 0.1 to 0.3 times the chord length of the aft foil $L_{c,\ af}$. The skilled person will understand that the amount of struts 8 may vary with the various embodiments of the present vessel 1 as shown in the Figures. The struts 8 and/or nacelles 11 may

furthermore be positioned at outer ends 18 of the aft foil 6 or at intermediate positions along the span-wise direction of the aft foil 6.

As shown in Figure 9, the nacelles 11 may be provided with one or more upwardly extending and/or downwardly extending winglets 12.

As shown in Figure 6, the struts 8 and/or the aft foil 6 may comprise one or more vortex generators 13 and/or interceptors 14 to postpone flow separation.

Preferably, the one or more vortex generators 13 and/or interceptors 14 are arranged near the second position 10. The vortex generators 13 are preferably positioned near the trailing edge of the aft foil 6. The interceptors 14 are preferably positioned near the leading edge of the aft foil 6. An example of an interceptor 14 is a Gurney flap, such as shown in Figure 6.

As shown in Figures 5, 8, 9 and 10, the two or more struts 8 may be provided with one or more anti-ventilation plates 15. Each of the two or more struts 8 may for instance comprise one, two, three, four or five anti-ventilation plates 15. Figure 5 for instance shows the presence of three anti-ventilation plates 15 per strut 8. Figures 8-10 show the presence of three anti-ventilation plates 15 per strut 8. Again, the amount of anti-ventilation plates 15 may vary across the range of embodiments of the present invention. As shown in Figure 5, the anti-ventilation plates 15 may be provided on the outer struts 8 only. However, Figure 8 shows an embodiment, wherein the anti-ventilation plates 15 are provided on both the outer struts 8, as well as the inner struts 8 (i.e. all struts are provided with anti-ventilation plates 15). Preferably, the anti-ventilation plates 15 are configured/positioned to be roughly at the waterline WL during operation.

As shown in Figures 8 to 10, the aft foil 6 may comprise two side aft foil parts 16 situated on opposing sides of the mirror plane S, in a direction transversal to the mirror plane S. The two side aft foil parts 16 may be separated (in a direction transversal to the mirror plane S), as shown in Figure 8, or connected, as shown in Figures 9 and 10.

As shown in Figures 9 and 10, the aft foil 6 may comprise a central aft foil part 17 situated at the mirror plane S, wherein the two side aft foil parts 16 are situated on opposing sides of the central aft foil part 17. The two side aft foil parts 16 may be connected by the central aft foil part 17. As shown in Figure 9, the central aft foil part 17 may have a central aft foil part chord length $L_{c,\ central}$ and the two side aft foil parts 16 have a side aft foil part chord length $L_{c,\ side}$, being different from the central

aft foil part chord length $L_{c,\ central}$. Preferably, the central aft foil part chord length $L_{c,\ central}$ is 60 to 90%, preferably around 75% of the side aft foil part chord length $L_{c,\ side}$. More preferably, the central aft foil part chord length $L_{c,\ central}$ is 30 to 40%, preferably around 35% of the side aft foil part chord length $L_{c,\ side}$. Even more preferably, the central aft foil part chord length $L_{c,\ central}$ is 5 to 15%, preferably around 10% of the side aft foil part chord length $L_{c,\ side}$. Preferably, the transition between the various chord lengths is smooth, such as shown in Figure 10. This is particularly advantageous when no interconnecting bodies, such as the nacelles 11 of Figure 9, are present between the side aft foil parts 16 and the central aft foil part 17.

As shown in Figure 10, one or more outer ends 18 of the aft foil 6, in a direction transversal to the mirror plane S, may comprise one or more upwardly extending and/or downwardly extending winglets 19.

Although not shown in any of the Figures, the aft foil 6 may furthermore have a quarter chord sweep angle Λ (not shown) of -30 to 30 degrees, preferably -15 to 15 degrees, more preferably -5 to 5 degrees. The aft foil 6 may have a maximum camber of 0.05 times, preferably 0.03 times, more preferably 0.01 times, the chord length $L_{c,\ af}$ of the asymmetric hydrofoil section. The two or more struts 8 may also be provided with backward sweep, such as a quarter chord sweep angle (not shown) of for instance 10 to 60 degrees, such as 20 to 50 degrees.

Another aspect of the invention concerns a computer-implemented method of designing an aforementioned vessel 1, comprising:

- providing a reference vessel V_{ref} with a hull 2 having a reference waterline length LWL_{ref} and a reference displacement D_{ref};
- increasing the reference waterline length LWL_{ref} at the aft hull portion 5, by 1 to 15%, preferably by 1 to 10%, more preferably by 1 to 5 %, most preferably by 1 to 3%, such as around 2%, of the reference waterline length LWL_{ref}, giving a hull 2 with a design waterline length LWL_{des};
- reducing the reference displacement D_{ref} of the hull 2 of the vessel 1 by removing volume at the aft hull portion 5 of the reference vessel V_{ref}, by 0.25 to 3%, preferably by 0.25 to 1.5%, more preferably by 0.25 to 0.75%, most preferably around 0.5%, of the reference displacement D_{ref}, giving a design displacement D_{des};
- designing the aft foil 6 to be affixed to the aft hull portion 5 with two or more connecting members 7, configured to be below the waterline WL during operation, spaced from the hull 2, and suitable for generating a lift force L_{af}, wherein

a span (b_{af}) of the aft foil (6) is at most 0.95 times a beam overall (BOA) of the vessel, the aft foil comprising a symmetric or asymmetric hydrofoil section, having positive camber, a lift coefficient ($C_{L,\,af}$) and a zero lift angle (α_0), as well as a chord (c_{af}) having a chord length ($L_{c,\,af}$),

wherein the aft foil 6 is affixed to the aft hull portion 5 in such a way, that, during operation, a free fluid surface FFS is present above the aft foil 6, and

wherein chord of the aft foil is configured to have a geometric angle (α_g) with respect to the horizontal plane (HP) equal to $180 / (2\pi^2) * l * C_{L,\,af} + \alpha_0 - k * \beta$, wherein k represents a factor taking into account the flattening of the flow below the aft portion at increasing distance from the aft portion, being between 0 and 1.25, and l represents a factor to compensate for the fact that the aft foil in practice is a three-dimensional object and not a two-dimensional one, being between 0 and 1.25.

Another aspect of the invention relates to a method of producing an aforementioned vessel 1, comprising the steps of:

- providing a hull 2, having a mirror plane S, designed for non-planing operation on the water body W, during operation displaying a waterline WL and having a forward direction X in a horizontal plane HP with a forward hull portion 3, an aft hull portion 5, having a buttock angle β, and a central hull portion 4, the hull 2 being configured to have the aft hull portion 5 with a smaller water displacement relative to a water displacement of the central hull portion 4; and
- affixing the aft foil 6 to the aft hull portion 5 with two or more connecting members 7, configured to be below the waterline WL during operation, spaced from the hull 2, and suitable for generating a lift force L_{af}, wherein a span (b_{af}) of the aft foil (6) is at most 0.95 times a beam overall (BOA) of the vessel, the aft foil comprising a symmetric or asymmetric hydrofoil section, having positive camber, a lift coefficient ($C_{L,\,af}$) and a zero lift angle (α_0), as well as a chord (c_{af}) having a chord length ($L_{c,\,af}$),

wherein the aft foil 6 is affixed to the aft hull portion 5 in such a way, that, during operation, a free fluid surface FFS is present above the aft foil 6, and

wherein the chord of the aft foil is configured to have a geometric angle (α_g) with respect to the horizontal plane (HP) equal to $180 / (2\pi^2) * l * C_{L,\,af} + \alpha_0 - k * \beta$, wherein k represents a factor taking into account the flattening of the flow below the aft portion at increasing distance from the aft portion, being between 0 and

1.25, and l represents a factor to compensate for the fact that the aft foil in practice is a three-dimensional object and not a two-dimensional one, being between 0 and 1.25.

Preferably, the method comprises the further steps of:

- designing the vessel 1 using the aforementioned method; and
- providing, such as producing, the hull 2 with the design waterline length LWL_{des} and the design displacement D_{des}.

It should be clear that the description above is intended to illustrate the operation of preferred embodiments of the invention, and not to reduce the scope of protection of the invention. Starting from the above description, many embodiments will be conceivable to the skilled person within the inventive concept and scope of protection of the present invention. It should furthermore be noted that many features are interchangeable between the illustrated embodiments. E.g. the anti-ventilation plates 15 shown with respect to the vessel 1 as shown in Figure 5 may also be implemented on the vessel 1 shown in Figures 1 to 4, although the anti-ventilation plates 15 are not explicitly shown in Figures 1 to 4. And although Figure 3 shows the presence of three struts 8, the skilled person will understand that e.g. two struts 8, such as shown in in Figure 4, could also be used. The same holds for the use of nacelles 11, vortex generators 13, interceptors 14, et cetera, which could, for instance, also be implemented on the vessel 1 shown in Figure 5, although such features are not explicitly disclosed in relation to Figure 5.

LIST OF REFERENCE NUMERALS

1. Vessel
2. Hull
3. Forward hull portion
4. Central hull portion
5. Aft hull portion
6. Aft foil
7. Connecting member
8. Strut
9. First connection position (strut)
10. Second connection position (strut)
11. Nacelle
12. Nacelle winglet
13. Vortex generator
14. Interceptor
15. Anti-ventilation plate
16. Side aft foil part
17. Central aft foil part
18. Outer end of aft foil
19. Aft foil winglet
20. Leading edge
21. Trailing edge

W	=	water body
WL	=	waterline
WS	=	water surface
X	=	forward direction
HP	=	horizontal plane
FFS	=	free fluid surface
VPSA	=	vertically projected surface area
S	=	mirror plane
IF	=	incoming flow

	AR_{af}	=	aspect ratio of aft foil
	c_{af}	=	chord of aft foil
	b_{af}	=	span of aft foil
	$L_{c,\ af}$	=	chord length of aft foil
	$L_{c,\ central}$	=	central aft foil part chord length
	$L_{c,\ side}$	=	side aft foil part chord length
	$L_{c,\ strut}$	=	chord length of aft foil
	L_{af}	=	lift force on aft foil
	$C_{L,\ af}$	=	lift coefficient of aft foil
	Λ	=	quarter-chord sweep angle
	V_{ref}	=	reference vessel
	LWL_{ref}	=	reference waterline length
	D_{ref}	=	reference displacement
	D_{ref}	=	design displacement
	LWL_{des}	=	design waterline length
	α	=	angle of attack at aft foil
	α_0	=	zero lift angle of aft foil
	α_g	=	geometric angle of aft foil with respect to horizontal plane
	β	=	buttock angle of aft portion

CLAIMS

1. Vessel (1) for operating on a body of water (W) comprising:

- a hull (2), having a mirror plane (S), designed for non-planing operation on the water body, during operation displaying a waterline (WL) and having a forward direction (X) in a horizontal plane (HP) with a forward portion (3), an aft portion (5), having a buttock angle (β), and a central portion (4), the hull being configured to have the aft portion with a smaller water displacement relative to a water displacement of the central portion; and

- an aft foil (6) affixed to the aft hull portion with two or more connecting members (7), configured to be below the waterline during operation, spaced from the hull, and suitable for generating a lift force (L_{af}), wherein a span (b_{af}) of the aft foil (6) is at most 0.95 times a beam overall (BOA) of the vessel, the aft foil comprising a symmetric or asymmetric hydrofoil section, having positive camber, a lift coefficient ($C_{L,\,af}$) and a zero lift angle (α_0), as well as a chord (c_{af}) having a chord length ($L_{c,\,af}$), wherein the aft foil is affixed to the aft hull portion in such a way, that during operation a free fluid surface (FFS) is present above the aft foil,

wherein the chord of the aft foil (6) is configured to have a geometric angle (α_g) with respect to the horizontal plane (HP) equal to $180 / (2\pi^2) * l * C_{L,\,af} + \alpha_0 - k * \beta$, wherein k represents a factor taking into account the flattening of the flow below the aft portion at increasing distance from the aft portion, being between 0 and 1.25, and l represents a factor to compensate for the fact that the aft foil in practice is a three-dimensional object and not a two-dimensional one, being between 0 and 1.25.

2. Vessel (1) according to claim 1, wherein the water body (W) displays a water surface (WS) during operation, wherein the free fluid surface area (FFS) is equal to at least 50%, preferably at least 75%, such as 100% of a vertically projected surface area (VPSA) of the aft foil (6) on the water surface.

3. Vessel (1) according to claim 1 or 2, wherein the aft foil (6) is arranged at a vertical distance below an extrapolated buttock angle line of at most 0.25 * the chord length ($L_{c,\,af}$) of the aft foil (6).

4. Vessel (1) according to any one of the preceding claims, wherein the aft foil (6) is configured to have a lift coefficient ($C_{L,\ af}$) of 0 to 1, such as 0.2 to 0.7.

5. Vessel (1) according to any one of the preceding claims, wherein, during operation, the aft foil is (6) configured to have an angle of attack (α) of -5 to 8 degrees with respect to an incoming flow (IF).

6. Vessel (1) according to any one of the preceding claims, wherein an aspect ratio (AR_{af}) of the aft foil (6) is 2 to 30 and/or wherein the span (b_{af}) of the aft foil (6) is 0.3 to 0.95 of a beam overall (BOA) of the vessel.

7. Vessel (1) according to any one of the preceding claims, wherein the aft foil (6) is affixed to the aft hull portion (5) with two or more connecting members (7) comprising two or more struts (8), wherein each of the two or more struts is affixed to the aft hull portion at a first position (9) and wherein each of the two or more struts is connected to the aft foil at a second position (10), wherein the aft foil (6) is preferably affixed to the aft hull portion (5) with two, three, four, five, six or seven struts (8) and/or wherein each of the two or more struts (8) has a chord length ($L_{c,\ strut}$) that varies from the first position (9) towards the second position (10), wherein more preferably each of the two or more struts (8) is tapered from the first position (9) towards the second position (10), wherein, more preferably, a taper ratio of each of the two or more struts (8) from the first position (9) towards the second position (10) is 0.5 to 2, preferably 0.7 to 1.5, more preferably 0.8 to 1.1.

8. Vessel (1) according to claim 7, wherein the aft foil (6) comprises a nacelle (11) at the second position (10) where each of the two or more struts (8) connects to the aft foil, wherein the nacelle (11) is preferably provided with one or more upwardly extending and/or downwardly extending winglets (12) and/or wherein each of the two or more struts (8) and/or the aft foil (6) comprises one or more vortex generators (13) and/or interceptors (14), wherein the one or more vortex generators (13) and/or interceptors (14) are preferably arranged near the second position (10) and/or wherein the two or more struts (8) are provided with one or more anti-ventilation plates (15), wherein each of the two or more struts may for instance comprise one, two, three, four or five anti-ventilation plates.

9. Vessel (1) according to any one of the preceding claims, wherein the aft foil (6) comprises two side aft foil parts (16) situated on opposing sides of the mirror plane (S), in a direction transversal to the mirror plane (S).

10. Vessel (1) according to claim 9, wherein the aft foil (6) comprises a central aft foil part (17) situated at the mirror plane (S), wherein the two side aft foil parts (16) are situated on opposing sides of the central aft foil part, wherein the two side aft foil parts are connected by the central aft foil part, wherein the central aft foil part (17) preferably has a central aft foil part chord length ($L_{c,\ central}$) and the two side aft foil parts (16) have a side aft foil part chord length ($L_{c,\ side}$), being different from the central aft foil part chord length ($L_{c,\ central}$), wherein the central aft foil part chord length ($L_{c,\ central}$) preferably is 60 to 90%, preferably around 75% of the side aft foil part chord length ($L_{c,\ side}$).

11. Vessel (1) according to any one of the preceding claims, wherein one or more outer ends (18) of the aft foil (6), in a direction transversal to the mirror plane (S), comprise one or more upwardly extending and/or downwardly extending winglets (19) and/or wherein the aft foil (6) has a quarter chord sweep angle (Λ) of -30 to 30 degrees, preferably -15 to 15 degrees, more preferably -5 to 5 degrees.

12. Vessel (1) according to any one of the preceding claims, wherein a maximum camber of the aft foil (6) is 0.05 times, preferably 0.03 times, more preferably 0.01 times, the chord length ($L_{c,\ af}$) of the asymmetric hydrofoil section.

13. Computer-implemented method of designing a vessel (1) according to any one of the preceding claims, comprising:

- providing a reference vessel (V_{ref}) with a hull (2) having a reference waterline length (LWL_{ref}) and a reference displacement (D_{ref});
- increasing the reference waterline length (LWL_{ref}) at the aft hull portion (5), by 1 to 15%, preferably by 1 to 10%, more preferably by 1 to 5 %, most preferably by 1 to 3%, such as around 2%, of the reference waterline length (LWL_{ref}), giving a hull with a design waterline length (LWL_{des});

- reducing the reference displacement (D_{ref}) of the hull of the vessel by removing volume at the aft hull portion of the reference vessel (V_{ref}), by 0.25 to 3%, preferably by 0.25 to 1.5%, more preferably by 0.25 to 0.75%, most preferably around 0.5%, of the reference displacement (D_{ref}), giving a design displacement (D_{des});
- designing the aft foil (6) to be affixed to the aft hull portion with two or more connecting members (7), configured to be below the waterline (WL) during operation, spaced from the hull, and suitable for generating a lift force (L_{af}), wherein a span (b_{af}) of the aft foil (6) is at most 0.95 times a beam overall (BOA) of the vessel, the aft foil comprising a symmetric or asymmetric hydrofoil section, having positive camber, a lift coefficient ($C_{L, af}$) and a zero lift angle (α_0), as well as a chord (c_{af}) having a chord length ($L_{c, af}$),

wherein the aft foil is affixed to the aft hull portion in such a way, that, during operation, a free fluid surface (FFS) is present above the aft foil, and

wherein chord of the aft foil is configured to have a geometric angle (α_g) with respect to the horizontal plane (HP) equal to $180 / (2\pi^2) * l * C_{L, af} + \alpha_0 - k * \beta$, wherein k represents a factor taking into account the flattening of the flow below the aft portion at increasing distance from the aft portion, being between 0 and 1.25, and l represents a factor to compensate for the fact that the aft foil in practice is a three-dimensional object and not a two-dimensional one, being between 0 and 1.25.

14. Method of producing a vessel (1) according to any one of the claims 1-12, comprising the steps of:

- providing a hull (2), having a mirror plane (S), designed for non-planing operation on the water body (W), during operation displaying a waterline (WL) and having a forward direction (X) in a horizontal plane (HP) with a forward hull portion (3), an aft hull portion (5), having a buttock angle (β), and a central hull portion (4), the hull being configured to have the aft hull portion with a smaller water displacement relative to a water displacement of the central hull portion; and
- affixing the aft foil (6) to the aft hull portion with two or more connecting members (7), configured to be below the waterline during operation, spaced from the hull, and suitable for generating a lift force (L_{af}), wherein a span (b_{af}) of the aft foil (6) is at most 0.95 times a beam overall (BOA) of the vessel, the aft foil comprising a symmetric or asymmetric hydrofoil section, having positive camber, a lift

coefficient ($C_{L,\ af}$) and a zero lift angle (α_0), as well as a chord (c_{af}) having a chord length ($L_{c,\ af}$),

wherein the aft foil is affixed to the aft hull portion in such a way, that, during operation, a free fluid surface (FFS) is present above the aft foil, and

wherein the chord of the aft foil is configured to have a geometric angle (α_g) with respect to the horizontal plane (HP) equal to $180 / (2\pi^2) * l * C_{L,\ af} + \alpha_0 - k * \beta$, wherein k represents a factor taking into account the flattening of the flow below the aft portion at increasing distance from the aft portion, being between 0 and 1.25, and l represents a factor to compensate for the fact that the aft foil in practice is a three-dimensional object and not a two-dimensional one, being between 0 and 1.25.

15. Method according to claim 14, comprising the further steps of:

- designing the vessel (1) using the method of claim 13; and
- providing, such as producing, the hull (2) with the design waterline length (LWL_{des}) and the design displacement (D_{des}).