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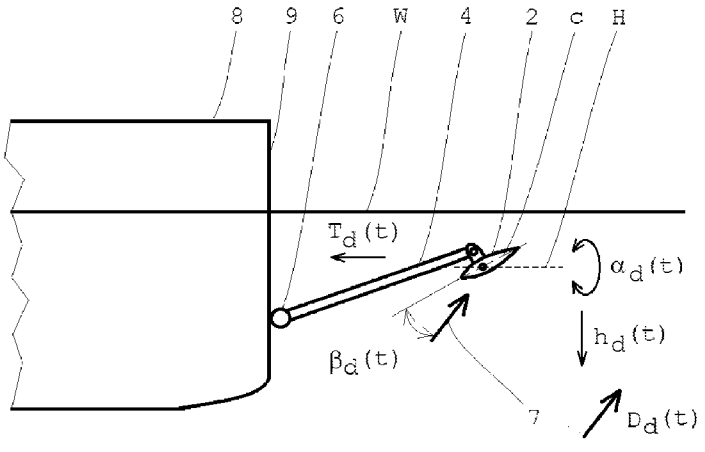



Fig. 1

(57) Abstract: The present invention concerns an oscillating foil propulsion system comprising at least one movable foil, at least one pitch mechanism connected to the at least one movable foil and configured to control a pitch motion of the at least one movable foil, at least one heave mechanism connected to the at least one movable foil and configured to control a downstroke heave motion and an upstroke heave motion of the at least one movable foil, and wherein the at least one pitch mechanism is configured to control a pitch angle of the at least one foil such that a thrust force and a drag force are obtained during a downstroke heave motion, and the at least one pitch mechanism is configured to control a pitch angle of the at least one foil such that an induced drag force during an upstroke heave motion is substantially smaller than the drag force during the downstroke heave motion. The invention further concerns a method for oscillating at least one movable foil.

# DUAL MODE OSCILLATING FOIL PROPULSION SYSTEM AND METHOD FOR OSCILLATING AT LEAST ONE MOVABLE FOIL

## TECHNICAL FIELD OF THE INVENTION:

[0001] The present invention relates to a marine propulsion system, in particular to an oscillating foil propulsion system including at least one movable foil. The invention further relates to a method for oscillating at least one movable foil in a fluid. Furthermore, the invention relates to a computer readable medium having stored thereon a set of computer implementable instructions. Additionally, the invention relates to a computer program.

## BACKGROUND OF THE INVENTION:

[0002] Different marine propulsion devices for use in a fluid are known, by means of which a vessel can be propelled. Typically vessels are equipped with at least one screw propeller for propulsion. The efficiency of the propeller is typically about 60 % to 70 %. In other words, 30 % to 40 % of the provided energy is lost. Further optimization of conventional screw propellers has become more difficult and therefore new propulsive devices are needed, which, for example, produce thrust by a movement of an oscillating fin, which mimics the manner in which whales or other animals swim. The efficiency of whales has been estimated to be about 80 % to 90 %. New fin propulsion systems may, for example, lead to achievement of a greater propulsor efficiency compared to a conventional screw propeller.

[0003] The document GB 1,092,839 discloses a steering and/or propelling means, which comprises a blade carrier pivotally secured to the stem of a boat above the water line and carrying a blade adapted to extend in its operative position below the water line, means by which the blade may be secured in a raised position, and means by which the blade may be oscillated from within the boat. The blade carrier may comprise an aft port hinged to a fore port which is pivotally secured to the stern of the boat and has a tiller attached thereto. The fore port has a vertical slot therein into which the blade is placed for use as a rudder and the aft port has a slot for the blade when it is desired to move it like a fish's tail by oscillating the tiller to propel the boat.

[0004] In J. Mattheijssens, J.-P. Marcel, W. Bosschaerts, D. Lefeber; Oscillating foils for ship propulsion; 9th National Congress on Theoretical and Applied Mechanics; Brussels; 9-10-11 May 2012 there is described a vertical, surface piercing, heaving and passively pitching hydrofoil mechanism as wells as a horizontal, heaving and passively pitching hydrofoil mechanism.

[0005] Additionally, according to H. Yamaguchi, N. Bose; Oscillating Foils for Marine Propulsion; The International Society of Offshore and Polar Engineers; ISBN 1-880653-10-9 and ISBN 1-880653-13-3; 1994 the propulsive efficiency of flexible foils can be greater than a comparable screw propeller.

SUMMARY OF THE INVENTION:

[0006] An object of certain embodiments of the present invention is to provide an oscillating foil propulsion system. A further object of certain embodiments of the present invention is to provide a method for oscillating at least one movable foil of a marine propulsion system. Furthermore, an object of certain embodiments of the present invention is to provide a computer readable medium having stored thereon a set of computer implementable instructions.

[0007] These and other objects are achieved by the embodiments of the present invention, as hereinafter described and claimed. According to an aspect of the invention, there is provided an oscillating foil propulsion system comprising at least one movable foil, at least one pitch mechanism connected to the at least one movable foil and configured to control a pitch motion of the at least one movable foil, at least one heave mechanism connected to the at least one movable foil and configured to control a downstroke heave motion and an upstroke heave motion of the at least one movable foil, and wherein the at least one pitch mechanism is configured to control a pitch angle of the at least one foil such that a thrust force and a drag force are obtained during the downstroke heave motion, and the at least one pitch mechanism is configured to control a pitch angle of the at least one foil such that an induced drag force during the upstroke heave motion is substantially smaller than the drag force during the downstroke heave motion.

[0008] The at least one pitch mechanism is self-adjusting or actively controllable. According to an embodiment, the at least one self-adjusting pitch mechanism

comprises at least one damper. According to another embodiment, the at least one actively controllable pitch mechanism comprises at least one hydraulic cylinder or at least one crank mechanism.

[0009] The system includes at least one connector, which is pivotally connected to a hinge mechanism and rotatably connected to the at least one movable foil. According to certain embodiments, the at least one heave mechanism includes at least one of the group: a hydraulic cylinder, rack and pinions, a worm screw, or swiveling joints. In an embodiment, the at least one heave mechanism is connected to the at last one connector.

[0010] According to an embodiment, the system is configured to move at least a portion of the at least one movable foil through a surface of a liquid during the downstroke heave motion and the upstroke heave motion.

[0011] According to another embodiment, the at least one movable foil is at least partially flexible.

[0012] In an embodiment, the system includes a first connector, which is connected to a first movable foil, and a second connector, which is connected to a second movable foil. According to a certain embodiment, the first connector and the second connector are movable connected to each other by a sliding mechanism. The sliding mechanism includes a coupling which is movable along the first connector and the second connector. In an embodiment, the heave mechanism is connected to the coupling and/or to at least one of the connectors.

[0013] According to another aspect, the invention also concerns a method for oscillating at least one movable

foil of a marine propulsion system, comprising the steps of:

- controlling a pitch angle of the at least one foil such that a thrust force and a drag force are obtained during a downstroke heave motion, and

- controlling a pitch angle of the at least one foil such that an induced drag force during an upstroke heave motion is substantially smaller than the drag force during the downstroke heave motion.

[0014] The pitch angle is controlled during the upstroke heave motion such that an angle of attack between an unsteady oncoming local fluid flow and a chord line of the at least one movable foil is substantially smaller than the drag force during the downstroke heave motion. According to an embodiment, the angle of attack during the upstroke heave motion is less than 5 degrees, preferably less than 3 degrees, and even more preferably essentially zero degrees. According to another embodiment, the velocity of the downstroke heave motion of the at least one movable foil is greater than the velocity of the upstroke heave motion.

[0015] In an embodiment, at least a portion of the at least one movable foil is moved through a surface of a liquid during the downstroke and upstroke heave motion.

[0016] According to certain embodiments, a pitch motion and a heave motion of a first movable foil and a second movable foil are controlled simultaneously and/or independently. In an embodiment, the pitch angle of a first movable foil is controlled during the downstroke heave motion and the pitch angle of a second movable foil is simultaneously controlled during the upstroke heave motion.

[0017] Aspects of the invention further concern a computer readable medium having stored thereon a set of computer implementable instructions capable of causing a computing device, in connection with a pitch mechanism capable of controlling a pitch motion of at least one movable foil and a heave mechanism capable of controlling a heave motion of the at least one movable foil, to vary a pitch angle of the at least one foil such that a thrust force and a drag force are obtained during a downstroke heave motion and that an induced drag force during an upstroke heave motion is substantially smaller than the drag force during the downstroke heave motion.

[0018] Further aspects of the invention concern a computer program configured to cause a method in accordance with at least one of claims 9 - 14 to be performed.

[0019] Considerable advantages are obtained by means of various embodiments of the present invention. An oscillating foil propulsion system is provided which implements aspects of the movement of a whale. Additionally, a method for oscillating at least one movable foil of a marine propulsion system is provided.

[0020] A vessel, for example a cargo vessel or a passenger vessel, can be propelled by means of the propulsion system according to the embodiments of the present invention. The required motion of the at least one foil is natural, continuously controllable and adjustable by modification of parameters. The pitch angles of the at least one movable foil are adjusted in order to obtain optimum thrust forces during the downstroke heave motion. The pitch angles of the movable foil are furthermore adjusted such that induced drag forces of the movable foil

are minimized during the upstroke heave motion, thus reducing the total ship resistance during operation of the propulsion system. According to certain embodiments, the movable foil may be additionally at least partially flexible to improve efficiency further. The efficiency improvement of a flexible or partially flexible foil is typically in the range between 3 % and 8 % compared to a rigid foil.

[0021] Model tests of a propulsion system according to an embodiment of the invention have indicated that a propulsor efficiency of 50 % - 70 % or greater can be achieved, which is in the range of or significantly greater than the efficiency of a conventional screw propeller. The efficiency of a conventional screw propeller is further more sensitive to a variation of the service speed and the sea margin than the efficiency of the oscillating foil. The wetted propulsion surface of the at least one foil can be additionally larger than the area of a conventional propeller which reduces the area load. The propulsion system is especially suited for so called horizontally positioned foils having a large aspect ratio in order to achieve advantageous lift and drag coefficients. In addition, the propulsion system according to the invention is suitable for vessels with limited draught, for example inland navigation vessels. The hydrofoil further reduces noise and vibrations.

[0022] According to certain embodiments the system includes at least one horizontal, heaving, pitching and surface piercing foil. The surface piercing arrangement enables a lower draught. Additionally, by turning the at least one foil at the most top position in the air less drag is created than by turning the at least one foil in

the liquid. The at least one foil can furthermore penetrate the fluid in the optimal angle of attack in the beginning of the downstroke heave motion.

BRIEF DESCRIPTION OF THE DRAWINGS:

[0023] For a more complete understanding of particular embodiments of the present invention and their advantages, reference is now made to the following descriptions, taken in conjunction with the accompanying drawings. In the drawings:

[0024] **Fig. 1** illustrates a schematic view of a propulsion system according to a first embodiment of the invention, wherein a movable foil is shown in a certain position during a downstroke heave motion,

[0025] **Fig. 2** illustrates a schematic view of a propulsion system according to a second embodiment of the invention, wherein a movable foil is shown in a certain position during an upstroke heave motion,

[0026] **Fig. 3** illustrates a schematic top view of a propulsion system according to a third embodiment of the invention,

[0027] **Fig. 4** illustrates a schematic top view of a propulsion system according to a fourth embodiment of the invention,

[0028] **Fig. 5** illustrates a schematic top view of a propulsion system according to a fifth embodiment of the invention,

[0029] **Fig. 6** illustrates a schematic time-vertical position-diagram of a propulsion system according to a sixth embodiment of the invention,

[0030] **Fig. 7** illustrates a schematic time-angle of attack-diagram of a propulsion system according to a seventh embodiment of the invention,

[0031] **Fig. 8** illustrates a schematic view of a propulsion system according to an eighth embodiment of the invention, wherein the system includes two foils, and

[0032] **Fig. 9** illustrates a schematic view of a propulsion system according to a ninth embodiment of the invention, wherein the system includes at least one surface piercing foil.

## DETAILED DESCRIPTION OF EMBODIMENTS OF THE INVENTION:

[0033] In **Fig. 1** a schematic view of a propulsion system 1 according to a first embodiment of the invention is illustrated, wherein a movable foil 2 is shown in a certain position during a downstroke heave motion $h_d(t)$. The system 1 includes a pitch mechanism and a heave mechanism which are not shown in Fig. 1. The pitch mechanism is connected to the movable foil 2 and configured to control a pitch angle $\alpha_d(t)$ of the movable foil 2. The pitch mechanism may be self-adjusting, i.e. passively controllable, or actively controllable. The heave mechanism is also connected to the movable foil 2 and configured to control a heave motion $h_d(t)$ of the movable foil 2 in a vertical direction. A connector 4 is pivotally secured to the stern 9 of a vessel 8 at one end by means of a hinge mechanism 6 and connected to the movable foil 2 at the

other end. The pitch angle $\alpha_d(t)$ of the movable foil 2 is adjusted such that optimum thrust forces $T_d(t)$ are obtained during the downstroke heave motion $h_d(t)$.

[0034] The force on a foil section set at an angle of incident to the local fluid flow can be resolved into two components, i.e. the lift L and the drag D. The equation of the lift force L of a foil can be written as:

$$L = \tfrac{1}{2} \rho v^2 C_L A \quad \text{, wherein}$$

L is the lift force, $\rho$ is the density of the fluid, v is the velocity of the foil relative to the local fluid flow, $C_L$ is the lift coefficient, and A is the area of the plan form of the foil. The most important parameters for the lift coefficient $C_L$ of a foil are the angle of attack between the chord line of the foil and the direction of the oncoming local fluid flow in the foil working area as well as the aspect ratio of the foil. The lift force L can be effectively maximized by increasing the angle of attack and reaches a maximum at a critical angle of attack. Increasing the angle of attack beyond the critical angle of attack leads to stalling of the foil as well as a decrease of the lift force. The critical angle of attack is in particular depending on the aspect ratio of the foil.

[0035] Therefore, sufficient pitch angles $\alpha_d(t)$ between the chord line c of the movable foil 2 and a horizontal plane H are provided during the downstroke heave motion $h_d(t)$ of the movable foil 2 in order to obtain sufficient angles of attack $ß_d(t)$ between the chord line c of the movable foil 2 and the oncoming local fluid flow 7 in the foil working area. The pitch angles $\alpha_d(t)$ during the downstroke heave motion $h_d(t)$ are controlled such that the angles of attack $ß_d(t)$ are in the range of but less than

the critical angle of attack of the movable foil 2, for example less than 20° or 15°. When starting, especially large downstroke heave amplitudes are necessary to create a local fluid flow 7 in the foil working area. The direction and velocity of the local fluid flow 7 in the foil working area are typically non-constant during a single downstroke heave motion of the at least one movable foil 2. In addition, the oncoming local fluid flow 7 in the foil working area is changing with increasing service speed of the vessel 8 from a rather vertical direction to a more horizontal direction and therefore continuous or step-wise adjustment of the pitch angles $\alpha_d(t)$ is advantageous in order to provide sufficient angles of attack $ß_d(t)$ during the downstroke heave motion $h_d(t)$ of the movable foil 2 and to obtain an optimal thrust $T_d(t)$ by maximizing the lift. Due to the periodic oscillating pitch and heave motion of the movable foil 2 the critical angle of attack may be further delayed. According to certain embodiments, the aspect ratio of the movable foil 2 may be, for example, greater than 2, 3, 4, or 5 in order to provide advantageous lift coefficients.

[0036] According to certain embodiments, the movable foil 2 may be flexible, in particular at least a portion of the rear part of the movable foil 2 may be flexible. A flexible foil can be more efficient than a rigid foil because of the rotation of the force vector during the downstroke heave motion $h_d(t)$ into a direction which is more in-line with the direction of advance. "Flexible foil" means that at least a portion of the foil deforms during the downstroke heave motion $h_d(t)$. The trailing edge of the foil may be deformed, for instance. The deformation is typically at least 1 cm. According to a certain embodiment, the movable foil 2 is water thigh and

light weight. The foil 2 may be, for example, made from aluminum. The deformation of the trailing edge of the foil may be, for example, 5 cm to 10 cm or more.

[0037] The power to the heave mechanism may be, for example, provided by means of hydraulic cylinders which are connected to the stern 9 of the vessel 8 and the connector 4. According to other embodiments, the power to the heave mechanism may be provided by rack and pinions which are driven hydraulically or electrically. Otherwise, it is also possible to provide the power to the heave mechanism by means of a worm screw which is driven hydraulically or electrically or by means of any other mechanism, for example by a device configured to swivel joints and torque arms.

[0038] In **Fig. 2** a schematic view of a propulsion system 1 according to a second embodiment of the invention is illustrated, wherein the movable foil 2 is shown in a certain position during an upstroke heave motion $h_u(t)$. The system 1 is adapted to change from a first heave mode, i.e. the downstroke heave $h_d(t)$, to a second heave mode, i.e. the upstroke heave $h_u(t)$. The motion of the at least one movable foil features different characteristics during the upstroke heave motion than during the downstroke heave motion. The pitch angles $\alpha_u(t)$ of the movable foil 2 are adjusted such that the induced drag forces $D_u(t)$ of the movable foil 2 are minimized or kept as small as possible during the upstroke heave motion $h_u(t)$. Creation of lift and thrust may take place but is not required during the upstroke heave motion. The total resistance of the system can be reduced by minimizing the drag forces $D_u(t)$ of the at least one movable foil 2, 3 during the upstroke heave motion $h_u(t)$.

[0039] The equation of a drag force of a foil can be written as:

$$D = \rho\, v^2\, C_D\, A \quad \text{, where}$$

D is the drag force, ρ is the density of the fluid, v is the velocity of the foil relative to the local fluid flow, $C_D$ is the drag coefficient, and A is the area of the plan form of the foil. The drag coefficient $C_D$ of a foil is depending on the angle of attack between the chord line of the foil and the direction of the oncoming local fluid flow in the foil working area.

[0040] Therefore, the drag forces $D_u(t)$ of the movable foil 2 can be effectively reduced by minimizing the angles of attack $ß_u(t)$ during the upstroke heave motion $h_u(t)$. The direction and velocity of the local fluid flow 7 in the foil working area are typically non-constant during a single upstroke heave motion of the at least one movable foil 2. The pitch angles $\alpha_u(t)$ during the upstroke heave motion $h_u(t)$ are preferably continuously or step-wise controlled such that the angles of attack $ß_u(t)$ are less than 5 degrees, preferably less than 3 or 2 degrees, and even more preferably essentially zero degrees. The pitch angles $\alpha_u(t)$ during the upstroke heave motion $h_u(t)$ are also depending on the speed of the vessel 8. With increasing service speed of the vessel 8 the oncoming local fluid flow 7 in the foil working area is changing from a rather vertical direction to a more horizontal direction. The drag forces $D_u(t)$ of the movable foil 2 can be also effectively reduced by means of consideration of the change of the direction and velocity of the local fluid flow 7 in the foil working area as well as continuous or step-wise controlled adjustment of the pitch angles $\alpha_u(t)$. The velocity of the upstroke heave motion $h_u(t)$ of the at least

one movable foil 2 may be further less than the velocity of the previous and/or subsequent downstroke heave motion $h_d(t)$ of the at least one movable foil 2. The drag forces $D_u(t)$ during the upstroke heave motion $h_u(t)$ are substantially smaller than the drag forces $D_d(t)$ during the downstroke heave motion $h_d(t)$.

[0041] In **Fig. 3** a schematic top view of a propulsion system 1 according to a third embodiment of the invention is illustrated. The system 1 is adapted to change from a first heave mode, i.e. the downstroke heave $h_d(t)$, to a second heave mode, i.e. the upstroke heave $h_u(t)$. The system 1 includes a pitch mechanism and a heave mechanism which are not shown in Fig. 3. A connector 4 is pivotally secured to the stern 9 of a vessel 8 at one end by means of a hinge mechanism 6. A first movable foil 2 and a second movable foil 3 are rotatably connected to the connector 4 at the other end. With the help of the pitch mechanism the pitch angles $\alpha_d(t)$ during the downstroke heave motion $h_d(t)$ and the pitch angles $\alpha_u(t)$ during the upstroke heave motion $h_u(t)$ can be adjusted. The adjustment of the two movable foils 2, 3 may take place simultaneously or independently. The pitch angles $\alpha_d(t)$, $\alpha_u(t)$ of the first foil 2 and the second foil 3 may be further equal or different. The system 1 is configured to create thrust $T_d(t)$ during the downstroke heave motion $h_d(t)$ and to reduce drag $D_u(t)$ during the upstroke heave motion $h_u(t)$. The taper ratio of the first movable foil 2 and the second movable foil 3, i.e. the minimum chord length $c_{min}$ in relation to the maximum chord length $c_{max}$, may be according to certain embodiments in the range between 0.2 and 0.7 in order to avoid an increase in induced drag due to a non-optimum taper ratio. Other embodiments may have other taper ratios, for example 1.1 or 1.3. According to certain embodiments,

the maximum chord length $c_{max}$ of the first movable foil 2 and the second movable foil is 2.5 m or less than 2.5 m, for example 1.4 m. Other embodiments may have a chord length greater than 2.5 m, for example 5.0 m or more.

[0042] In **Fig. 4** a schematic top view of a propulsion system 1 according to a fourth embodiment of the invention is illustrated. The system 1 is adapted to change from a first heave mode, i.e. the downstroke heave $h_d(t)$, to a second heave mode, i.e. the upstroke heave $h_u(t)$. The system 1 is configured to create thrust $T_d(t)$ during the downstroke heave motion $h_d(t)$ and to reduce drag $D_u(t)$ during the upstroke heave motion $h_u(t)$. The first movable foil 2 and the second movable foil 3 each sweep backwards. The sweep back angles of the first and second movable foil 2, 3 are typically less than 45°, preferably between 10° and 30°, for example 15°. Depending on the sweep back angle an optimum taper ratio can be then determined. With increasing sweep back angle lower taper ratios can be chosen. Taper ratios lower than 0.2 are typically not recommended. Certain embodiments may have a taper ratio lower than 0.2. The first movable foil 2 and the second movable foil may be additionally equipped with so called end plates or winglets which are not shown in Fig. 4. According to other embodiments of the invention the first movable foil 2 and the second movable foil 3 may form a continuous single foil to avoid a gap between the two movable foils 2, 3.

[0043] In **Fig. 5** a schematic top view of a propulsion system 1 according to a fifth embodiment of the invention is illustrated. The system 1 is adapted to change from a first heave mode, i.e. the downstroke heave $h_d(t)$, to a second heave mode, i.e. the upstroke heave $h_u(t)$. The

system 1 is configured to create thrust $T_d(t)$ during the downstroke heave motion $h_d(t)$ and to reduce drag $D_u(t)$ during the upstroke heave motion $h_u(t)$. The movable foil 2 of the propulsion system 1 includes aspects of the shape of a fluke plan form of an animal. The system 1 further includes a computer readable medium having stored thereon a set of computer implementable instructions capable of causing a computing device 11, in connection with a pitch mechanism capable of controlling a pitch motion of at the least one movable foil and a heave mechanism capable of controlling a heave motion of the at least one movable foil, to vary a pitch angle $\alpha_d(t)$, $\alpha_u(t)$ of the at least one foil such that a thrust force ($T_d(t)$) and a drag force $D_d(t)$ are obtained during a downstroke heave motion $h_d(t)$ and that a drag force $D_u(t)$ during an upstroke heave motion $h_u(t)$ is substantially smaller than the drag force $D_d(t)$ during the downstroke heave motion $h_d(t)$. The system 1 allows controlled adjustment of the downstroke heave $h_d(t)$, the upstroke heave $h_u(t)$, the frequency of the downstroke heave $h_d(t)$, the frequency of the upstroke heave $h_u(t)$, the amplitude of the downstroke heave $h_d(t)$, the amplitude of the upstroke heave $h_u(t)$, the pitch angle $\alpha_d(t)$ during the downstroke heave $h_d(t)$, the pitch angle $\alpha_u(t)$ during the upstroke heave $h_u(t)$, the frequency of the pitch angle $\alpha_d(t)$ during the downstroke heave $h_d(t)$, the frequency of the pitch angle $\alpha_u(t)$ during the upstroke heave $h_u(t)$, the amplitude of the pitch angle $\alpha_d(t)$ during the downstroke heave $h_d(t)$, and the amplitude of the pitch angle $\alpha_u(t)$ during the upstroke heave $h_u(t)$ by means of the pitch mechanism and the heave mechanism. The frequency of the sinusoidal like heave motion is typically less than 3 Hz. Maximum pitch angles $\alpha_d(t)$ during the downstroke heave $h_d(t)$ and maximum pitch angles $\alpha_u(t)$ during the upstroke

heave $h_u(t)$ are typically in the range between 70° and 0°, 60° and 0°, 50° and 0°, 40° and 0°, 30° and 0°, 20° and 0°, or 10° and 0°. According to certain embodiments the fluke plan form may include aspects of the shape of a whale or any other animal, for example the shape of a white whale, a mink whale, or a fin whale.

[0044] In **Fig. 6** a schematic time-vertical position-diagram of a propulsion system according to a sixth embodiment of the invention is illustrated. The system is adapted to change from a first heave mode, i.e. the downstroke heave $h_d(t)$, to a second heave mode, i.e. the upstroke heave $h_u(t)$. The motion of the at least one movable foil features different characteristics during the first mode and the second mode. The velocity of the downstroke heave $h_d(t)$ is significantly greater than the velocity of the upstroke heave $h_u(t)$ in order to obtain optimum thrust forces $T_d(t)$ during the downstroke heave $h_d(t)$ and minimized drag forces $D_u(t)$ during the upstroke heave $h_u(t)$.

[0045] In **Fig. 7** a schematic time-angle of attack-diagram of a propulsion system according to a seventh embodiment of the invention is illustrated. The system is adapted to change from a first heave mode, i.e. the downstroke heave $h_d(t)$, to a second heave mode, i.e. the upstroke heave $h_u(t)$. The motion of the at least one movable foil features different characteristics during the first mode and the second mode.

[0046] Sufficient pitch angles $\alpha_d(t)$ between the chord line c of the movable foil 2 and a horizontal plane H are provided during the downstroke heave motion $h_d(t)$ of the movable foil 2 in order to obtain sufficient angles of attack $ß_d(t)$ between the chord line c of the movable foil 2

and the oncoming local fluid flow 7 in the foil working area. According to certain embodiments, the pitch angles $\alpha_d(t)$ during the downstroke heave motion $h_d(t)$ are controlled such that the angles of attack $ß_d(t)$ are in the range of but less than the critical angle of attack $ß_{crit}$ of the movable foil 2, for example, less than 20° or 15°. Optimum thrust $T_d(t)$ is created during the downstroke heave motion $h_d(t)$. According to certain embodiments, the angles of attack $ß_d(t)$ during the downstroke heave motion $h_d(t)$ can be greater than the critical angle of attack $ß_{crit}$ of the movable foil 2.

[0047] The pitch angles $\alpha_u(t)$ during the upstroke heave motion $h_u(t)$ are continuously or step-wise controlled such that the angles of attack $ß_u(t)$ are less than 5 degrees, preferably less than 3 or 2 degrees, and more preferably essentially zero degrees. Due to the unsteady local fluid flow 7 in the foil working area the angles of attack $ß_u(t)$ oscillate within a certain range, for example between +1° and -1°, during the upstroke heave $h_u(t)$. The work done by the drag force $D_d(t)$ during the downstroke heave motion $h_d(t)$ is significantly greater than the work done by the induced drag force $D_u(t)$ during the upstroke heave motion $h_u(t)$.

[0048] In **Fig. 8** a schematic view of a propulsion system 1 according to an eighth embodiment of the invention is illustrated. The system 1 includes a first movable foil 2 and a second movable foil 3 which are pivotally secured to the stern 9 of a vessel 8 via a first connector 4 and a second connector 5, respectively. The first connector 4 and the second connector 5 are movable connected to each other by a sliding mechanism. The sliding mechanism includes a coupling 10 which is movable along the first connector 4

and the second connector 5. The system 1 further includes at least one heave mechanism which is connected to at least one of the two connectors 4, 5 or to the coupling 10 of the sliding mechanism. A linear movement of the coupling 10 along the first connector 4 and the second connector 5 leads to the downstroke heave motion $h_d(t)$ of the first movable foil 2 and to a simultaneous upstroke heave motion $h_u(t)$ of the second movable foil 3. The pitch angles $\alpha_d(t)$ of the first movable foil 2 are adjusted to obtain optimum thrust forces $T_d(t)$ during the downstroke heave motion $h_d(t)$. The pitch angles $\alpha_u(t)$ of the second movable foil 3 are adjusted such that minimum drag forces $D_u(t)$ of the second movable foil 3 are induced during the upstroke heave motion $h_u(t)$. Changing the direction of the movement of the coupling 10 along the first connector 4 and the second connector 5 leads to a downstroke heave motion $h_u(t)$ of the second movable foil 3 and to a simultaneous upstroke heave motion $h_d(t)$ of the first movable foil 2. The pitch angles $\alpha_d(t)$ of the second movable foil 3 are then adjusted to obtain optimum thrust forces $T_d(t)$ during the downstroke heave motion $h_d(t)$ and the pitch angles $\alpha_u(t)$ of the first movable foil 2 are adjusted such that the induced drag forces $D_u(t)$ of the second movable foil 3 are minimized during the upstroke heave motion $h_u(t)$. Additionally, the system 1 includes two pitch mechanisms which are connected to the movable foils 2, 3 and configured to control a pitch motion of the respective movable foil 2, 3. The pitch mechanisms and the heave mechanism are not shown in Fig. 8. According to certain other embodiments, the first movable foil 2 and the second movable foil 3 are not connected by a sliding means and move simultaneously in the same direction. The first movable foil 2 and the second movable foil 3 are then arranged in vertical direction one above

the other. There may be even more than two foils arranged in vertical direction.

[0049] **Fig. 9** illustrates a schematic view of a propulsion system 1 according to a ninth embodiment of the invention, wherein the system 1 includes a horizontal, heaving, pitching and surface piercing foil. The system 1 includes a first movable foil 2 and a second movable foil 3 and two pitch mechanisms which are connected to the respective movable foils 2, 3 and configured to control a pitch angle $\alpha_d(t)$, $\alpha_u(t)$ during a downstroke heave motion $h_d(t)$ and an upstroke heave motion $h_u(t)$. The system 1 further includes a first connector 4, which is connected to the first movable foil 2, and a second connector 5, which is connected to the second movable foil 3. The first connector 4 and the second connector 5 are each pivotally connected to a hinge mechanism 6 at one end. The hinge mechanisms 6 are connected to a stern 9 of a vessel 8. The first connector and the second connector are furthermore connected to each other by a sliding mechanism, which includes a coupling 10, which is movable along the first connector 4 and the second connector 5. The coupling 10 is connected to a heave mechanism which is configured to control a downstroke heave motion $h_d(t)$ and an upstroke heave motion $h_u(t)$ of the movable foils 2, 3. According to an embodiment, at least one hydraulic cylinder is connected to the coupling 10 at one end. The at least one hydraulic cylinder is then connected to one of the connectors 4, 5 or to the vessel 8. A linear movement of the coupling 10 along the first connector 4 and the second connector 5 leads to the downstroke heave motion $h_d(t)$ of one of the movable foils 2, 3 and to a simultaneous upstroke heave $h_u(t)$ motion of the other movable foil 2, 3 and vice versa. The heave motion of each movable foil 2, 3 is preferably

sinusoidal like. In Fig. 9 the amplitudes of the heave motion of the first movable foil 2 and the second movable foil 3 are at the system´s maximum. The first movable foil 2 is partially arranged above the waterline W. The first movable foil 2 represents a horizontal, heaving, pitching and surface piercing foil. The pitch mechanisms are configured to control the pitch angles $\alpha_d(t)$ of the first movable foil 2 and the second movable foil 3 in order to obtain a thrust force $T_d(t)$ during the downstroke heave motion $h_d(t)$. Additionally, there are obtained drag forces $D_d(t)$ during the downstroke heave $h_d(t)$. The pitch mechanisms are further configured to control the pitch angles $\alpha_u(t)$ of the first movable foil 2 and the second movable foil 3 in order to minimize an induced drag force $D_u(t)$ during the upstroke heave motion $h_u(t)$. The pitch angles $\alpha_u(t)$ of the movable foils 2, 3 are controlled during the upstroke heave motion $h_u(t)$ such that an angle of attack $ß_u(t)$ between an oncoming local fluid flow 7 in the foil working area and a chord line c of the respective foils 2, 3 is reduced. According to certain embodiments, the angle of attack $ß_u(t)$ is during the upstroke heave motion $h_u(t)$ typically less than 5°, preferably less than 3°, and more preferably essentially zero degrees. The system 1 is configured to move at least a portion of the first foil 2 through the waterline W during the downstroke heave motion $h_d(t)$ and the upstroke heave motion $h_u(t)$. Additionally, the first movable foil 2 and the second movable foil 3 may be partially flexible in order to rotate the resultant force vector during the downstroke heave motion $h_d(t)$ into a direction more in-line with the direction of advance.

[0050] Although the present invention has been described in detail for the purpose of illustration,

various changes and modifications can be made within the scope of the claims. In addition, it is to be understood that the present disclosure contemplates that, to the extent possible, one or more features of any embodiment may be combined with one or more features of any other embodiment.

[0051] It is to be understood that the embodiments of the invention disclosed are not limited to the particular structures, process steps, or materials disclosed herein, but are extended to equivalents thereof as would be recognized by those ordinarily skilled in the relevant arts. It should also be understood that terminology employed herein is used for the purpose of describing particular embodiments only and is not intended to be limiting.

[0052] In particular, the disclosed embodiments are not limited to controlling the pitch angle of the at least one foil such that a thrust force is obtained during the downstroke heave motion. Thrust may be also created during the upstroke heave motion of the at least one movable foil and drag may be minimized during the downstroke heave motion.

[0053] The drag force $D_d(t)$ during the downstroke heave, the drag force $D_u(t)$ during the upstroke heave, the thrust force $T_d(t)$ during the downstroke heave, the downstroke heave $h_d(t)$, the upstroke heave $h_u(t)$, the pitch angle $\alpha_d(t)$ during the downstroke heave, the pitch angle $\alpha_u(t)$ during the upstroke heave, the angle of attack $\beta_d(t)$ during the downstroke heave, and the angle of attack $\beta_u(t)$ during the upstroke heave are functions of time.

[0054] In general, the vertical direction is defined as being perpendicular to the horizontal direction

and the transversal direction. The horizontal direction is further defined as being perpendicular to the transversal direction. The horizontal direction and the transversal direction form a horizontal plane. A rotation of one of the aforementioned directions about at least one axis of rotation leads to a rotation of the other two directions as well as to a rotation of the horizontal plane about the at least one axis of rotation within the meaning of the detailed description of embodiments.

**List of reference numbers:**

| | |
|---|---|
| 1 | propulsion system |
| 2 | first movable foil |
| 3 | second movable foil |
| 4 | first connector |
| 5 | second connector |
| 6 | hinge mechanism |
| 7 | local fluid flow |
| 8 | vessel |
| 9 | stern |
| 10 | coupling |
| 11 | computing device |
| c | chord line |
| $c_{max}$ | maximum chord length |
| $c_{min}$ | minimum chord length |
| $D_d(t)$ | drag force during downstroke heave |
| $D_u(t)$ | drag force during upstroke heave |
| $F_d(t)$ | thrust force during downstroke heave |
| H | horizontal plane |
| $h_d(t)$ | downstroke heave |
| $h_u(t)$ | upstroke heave |
| W | waterline |

$\alpha_d(t)$ pitch angle during downstroke heave

$\alpha_u(t)$ pitch angle during upstroke heave

$ß_{crit}$ critical angle of attack

$\beta_d(t)$ angle of attack during downstroke heave

$\beta_u(t)$ angle of attack during upstroke heave

**Claims:**

1. An oscillating foil propulsion system (1) comprising:

- at least one movable foil (2, 3),

- at least one pitch mechanism connected to the at least one movable foil (2, 3) and configured to control a pitch motion of the at least one movable foil (2, 3),

- at least one heave mechanism connected to the at least one movable foil (2, 3) and configured to control a downstroke heave motion ($h_d(t)$) and an upstroke heave motion ($h_u(t)$) of the at least one movable foil (2, 3), and

- wherein the at least one pitch mechanism is configured to control a pitch angle ($\alpha_d(t)$) of the at least one foil (2, 3) such that a thrust force ($T_d(t)$) and a drag force ($D_d(t)$) are obtained during the downstroke heave motion ($h_d(t)$), and

- the at least one pitch mechanism is configured to control a pitch angle ($\alpha_u(t)$) of the at least one foil (2, 3) such that an induced drag force ($D_u(t)$) during the upstroke heave motion ($h_u(t)$) is substantially smaller than the drag force ($D_d(t)$) during the downstroke heave motion ($h_d(t)$).

2. The oscillating foil propulsion system (1) according to claim 1, wherein

- the at least one pitch mechanism is self-adjusting and comprises at least one damper, or

- the at least one pitch mechanism is actively controllable and comprises at least one hydraulic cylinder or at least one crank mechanism.

3. The oscillating foil propulsion system (1) according to claim 1 or 2, wherein the system (1) includes at least one connector (4, 5) which is pivotally connected to a hinge mechanism (6) and rotatably connected to the at least one movable foil (2, 3).

4. The oscillating foil propulsion system (1) according to claim 3, wherein the at least one heave mechanism is connected to the at last one connector (4, 5).

5. The oscillating foil propulsion system (1) according to any of claims 1 to 4, wherein the system (1) is configured to move at least a portion of the at least one movable foil (2, 3) through a surface (W) of a liquid during the downstroke heave motion ($h_d(t)$) and the upstroke heave motion ($h_u(t)$).

6. The oscillating foil propulsion system (1) according to any of claims 1 to 5, wherein the at least one movable foil (2, 3) is at least partially flexible.

7. The oscillating foil propulsion system (1) according to any of claims 1 to 6, wherein

- the system (1) includes a first connector (4), which is connected to a first movable foil (2), and a second connector (5), which is connected to a second movable foil (3), and

- the first connector (4) and the second connector (5) are movable connected to each other by a sliding mechanism.

8. The oscillating foil propulsion system (1) according to claim 7, wherein

- the sliding mechanism includes a coupling (10) which is movable along the first connector (4) and the second connector (5), and

- the at least one heave mechanism is connected to the coupling and/or to at least one of the connectors (4, 5).

9. A method for oscillating at least one movable foil of a marine propulsion system, comprising the steps of:

- controlling a pitch angle ($\alpha_d(t)$) of the at least one foil such that a thrust force ($T_d(t)$) and a drag force ($D_d(t)$) are obtained during a downstroke heave motion ($h_d(t)$), and

- controlling a pitch angle ($\alpha_u(t)$) of the at least one foil such that an induced drag force ($D_u(t)$) during an upstroke heave motion ($h_u(t)$) is substantially smaller than the drag force ($D_d(t)$) during the downstroke heave motion ($h_d(t)$).

10. The method according to claim 9, wherein the pitch angle $\alpha_u(t)$ is controlled during the upstroke heave motion such that an angle of attack $ß_u(t)$ between an unsteady oncoming local fluid flow and a chord line of the at least one movable foil is reduced.

11. The method according to claim 10, wherein the angle of attack $ß_u(t)$ during the upstroke heave motion ($h_u(t)$) is less than 5 degrees, preferably less than 3 or 2 degrees, and more preferably essentially zero degrees.

12. The method according to any of the claims 9 to 11, wherein the velocity of the downstroke heave motion of the

at least one movable foil is greater than the velocity of the upstroke heave motion.

13. The method according to any of the claims 9 to 12 wherein at least a portion of the at least one movable foil is moved through a surface of a liquid during the downstroke and upstroke heave motion.

14. The method according to any of the claims 9 to 13, wherein the pitch angle ($\alpha_d(t)$) of a first movable foil is controlled during the downstroke heave motion ($h_d(t)$) and the pitch angle ($\alpha_u(t)$) of a second movable foil is simultaneously controlled during the upstroke heave motion ($h_u(t)$).

15. A computer readable medium having stored thereon a set of computer implementable instructions capable of causing a computing device, in connection with a pitch mechanism capable of controlling a pitch motion of at least one movable foil and a heave mechanism capable of controlling a heave motion of the at least one movable foil, to vary a pitch angle ($\alpha_d(t)$, $\alpha_u(t)$) of the at least one foil such that a thrust force ($T_d(t)$) and a drag force ($D_d(t)$) are obtained during a downstroke heave motion ($h_d(t)$) and that an induced drag force ($D_u(t)$) during an upstroke heave motion ($h_u(t)$) is substantially smaller than the drag force ($D_d(t)$) during the downstroke heave motion ($h_d(t)$).

16. A computer program configured to cause a method in accordance with at least one of claims 9 - 14 to be performed.

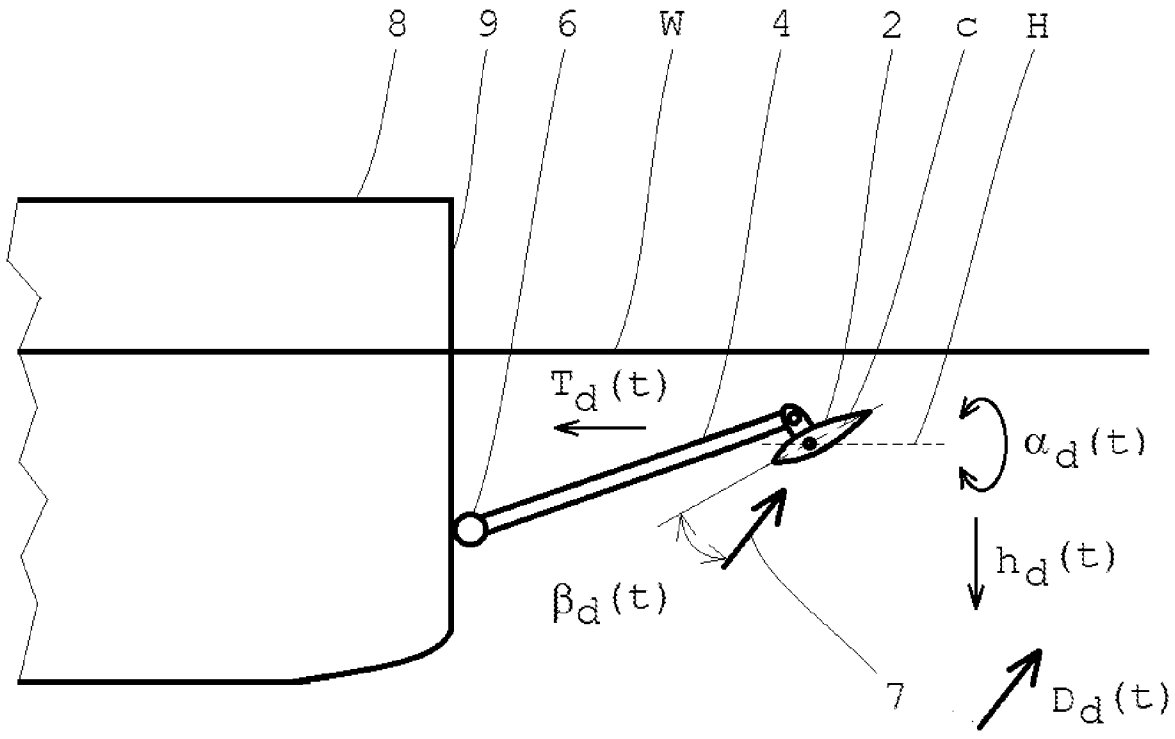



Fig. 1

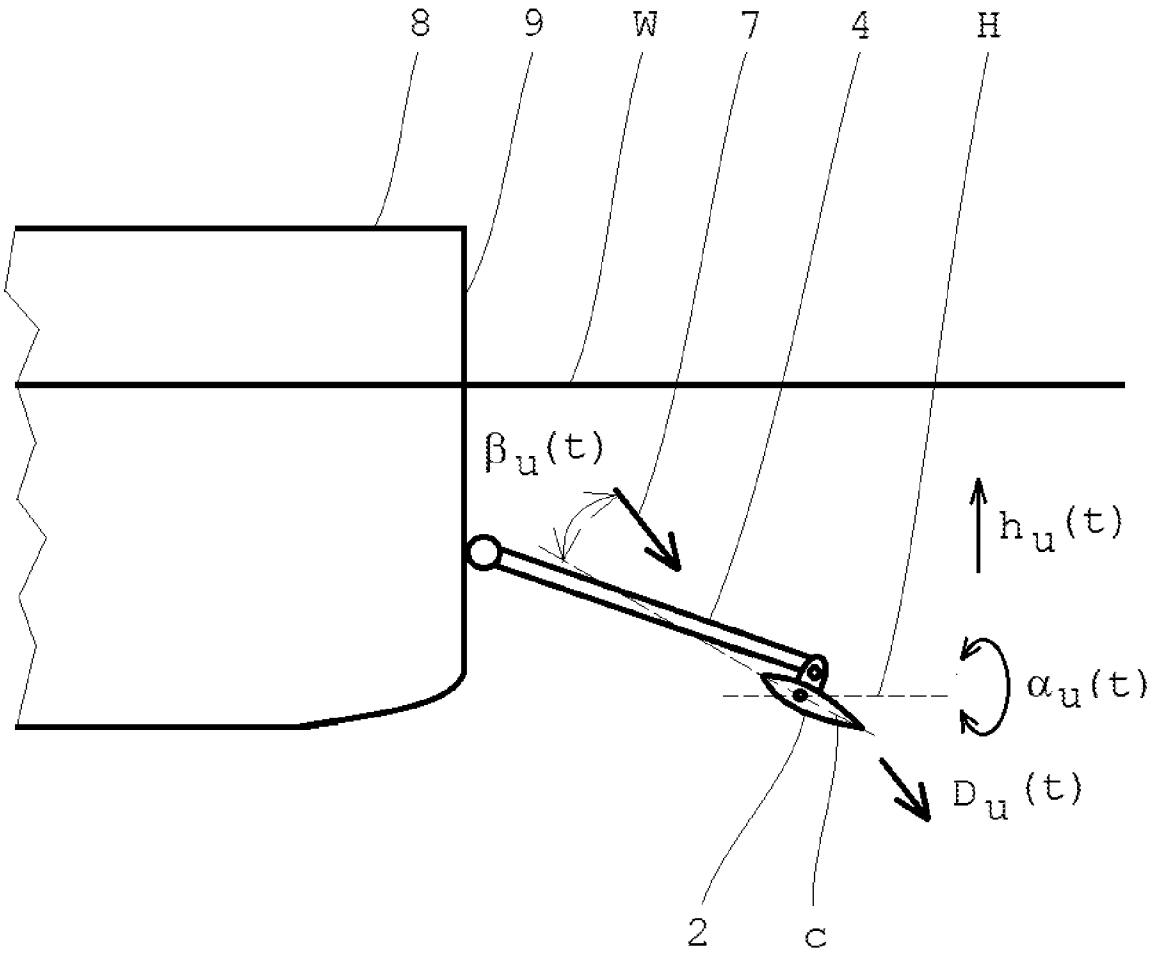



Fig. 2

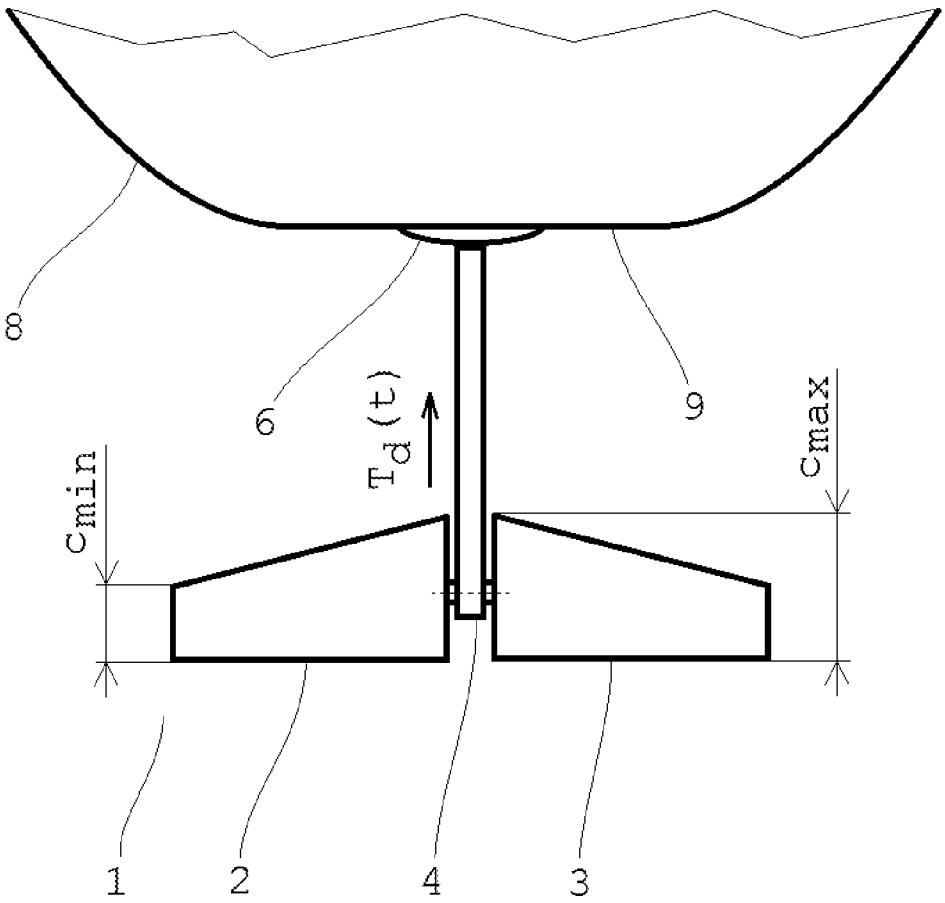



Fig. 3

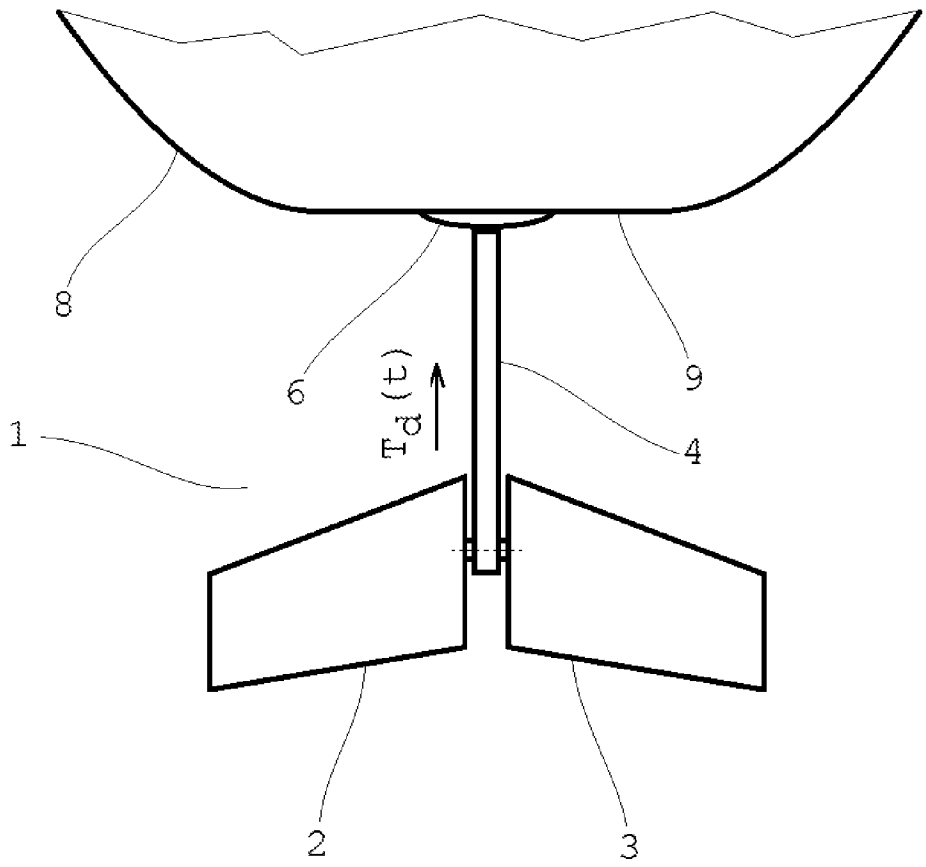



Fig. 4

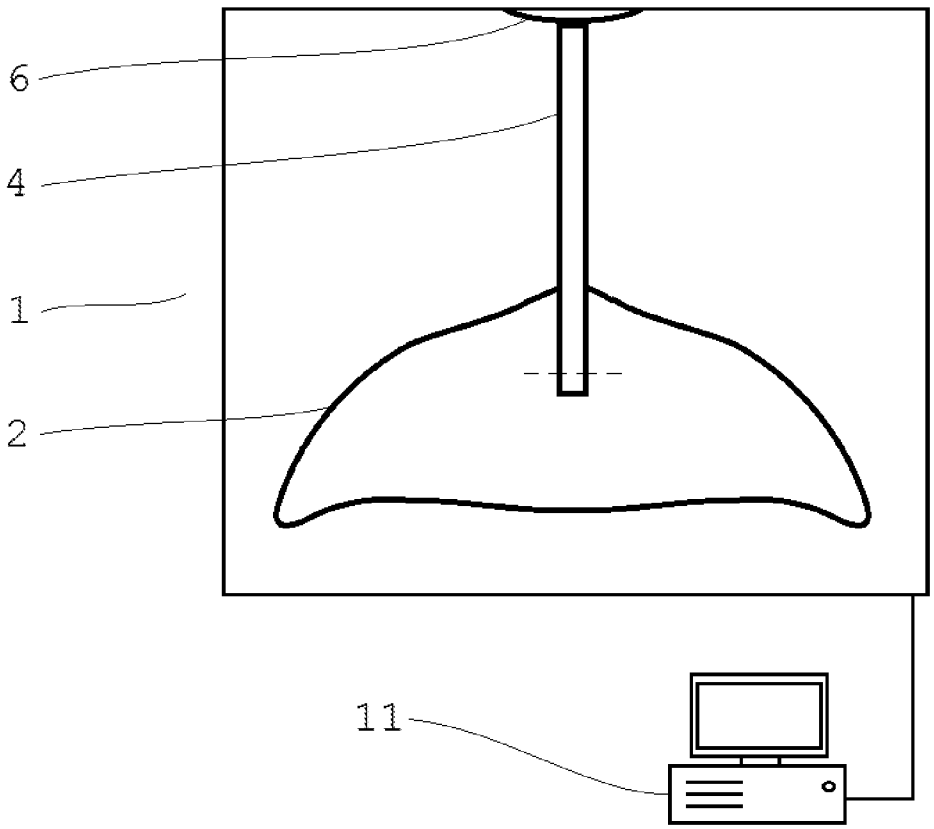



Fig. 5

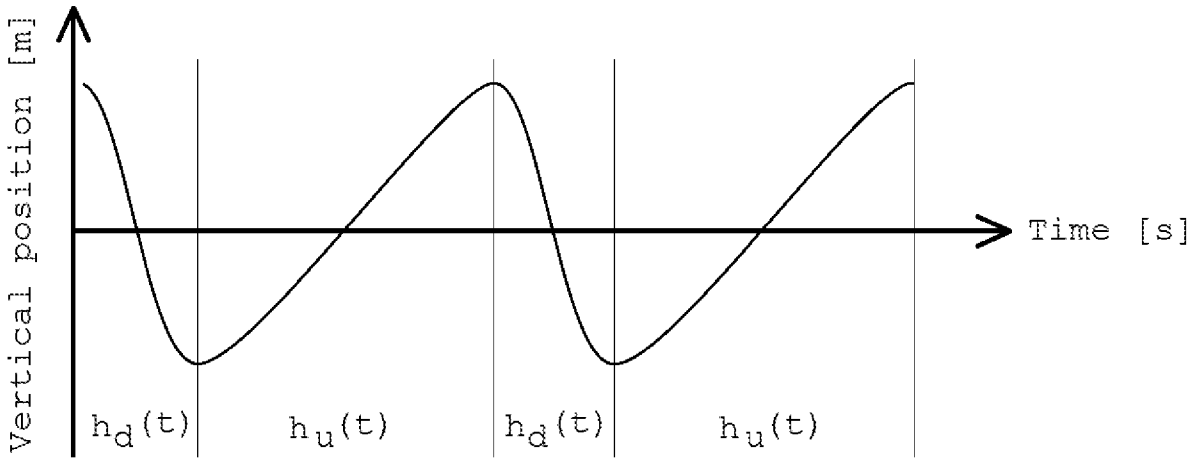

Vertical position [m]
Time [s]
$h_d(t)$
$h_u(t)$
$h_d(t)$
$h_u(t)$

Fig. 6

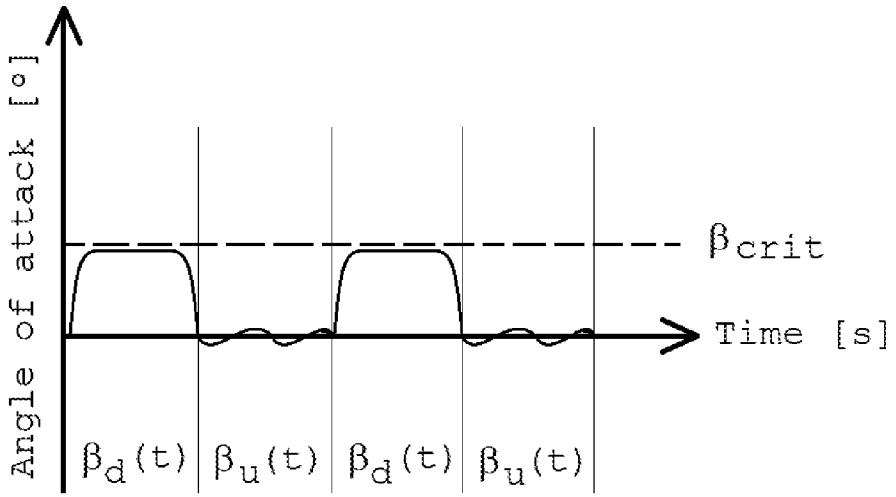

Angle of attack [°]
$\beta_{crit}$
Time [s]
$\beta_d(t)$
$\beta_u(t)$
$\beta_d(t)$
$\beta_u(t)$

Fig. 7

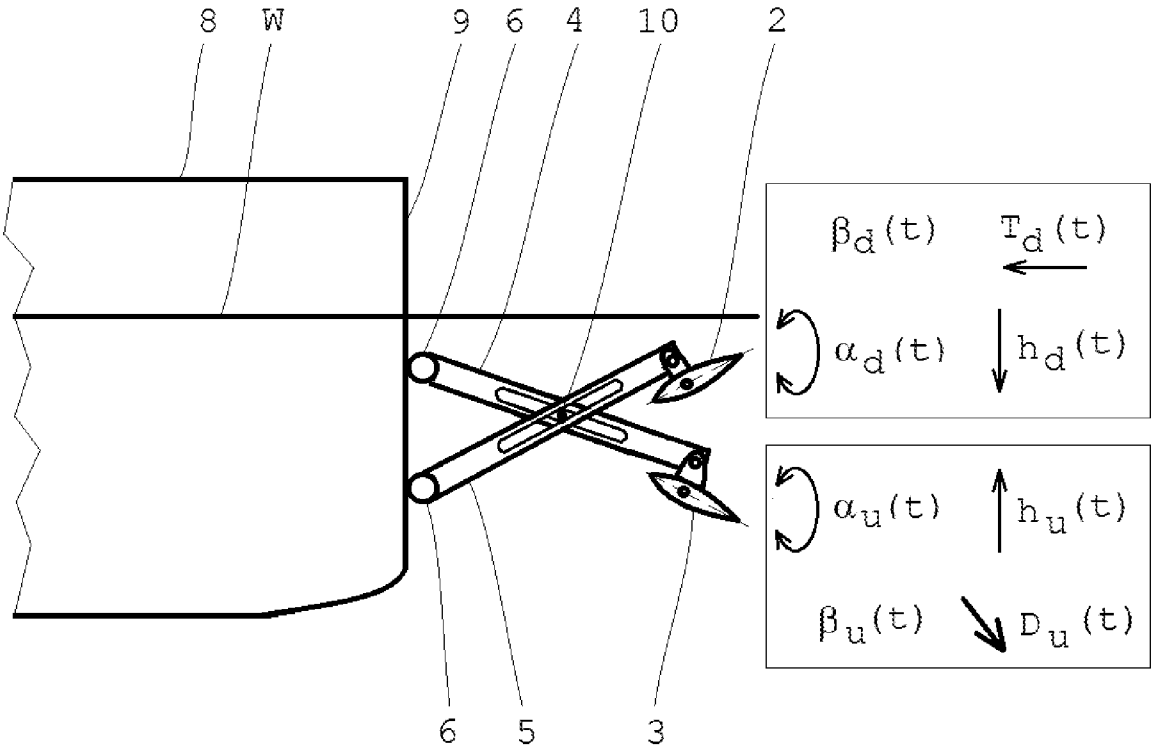



Fig. 8

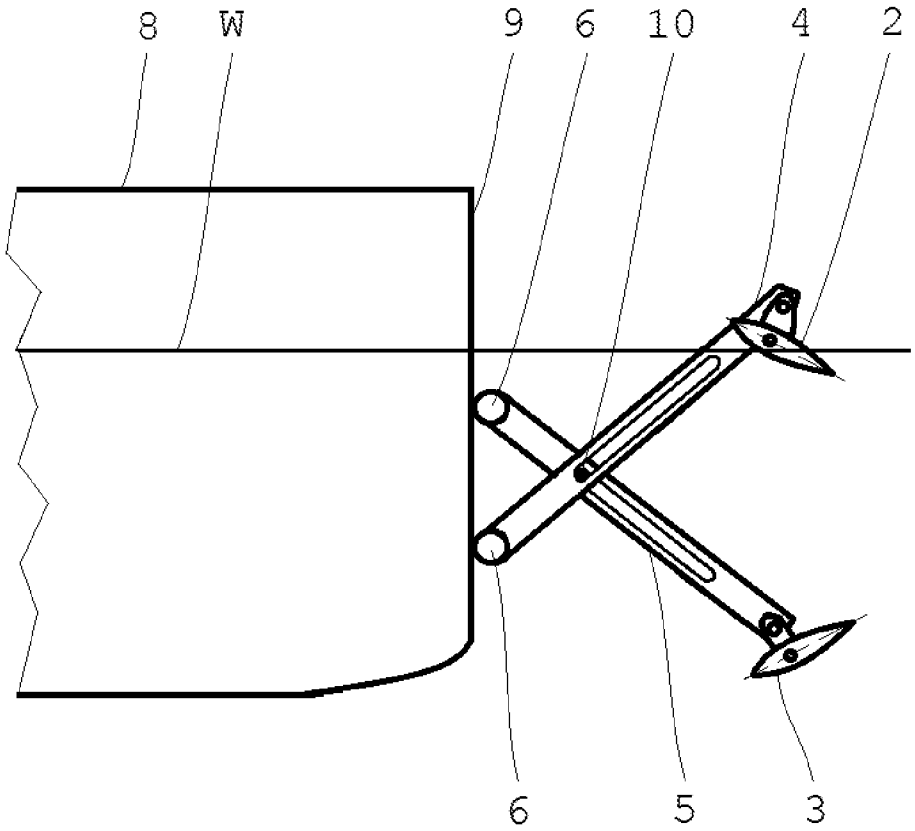



Fig. 9

**INTERNATIONAL SEARCH REPORT**

International application No.
PCT/FI2015/050507

A. **CLASSIFICATION OF SUBJECT MATTER**

See extra sheet

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC: B63H

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

FI, SE, NO, DK

Electronic data base consulted during the international search (name of data base, and, where practicable, search terms used)

EPO-Internal, WPI

C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| X | WO 2011115475 A2 (GORIS BAS DOING BUSINESS AS OSCILLATING FOIL DEV [NL]) 22 September 2011 (22.09.2011)<br>whole document; figures | 1-6, 9-11, 13-16 |
| X | WO 2010021541 A2 (GORIS BAS DOING BUSINESS AS OS [NL])<br>25 February 2010 (25.02.2010)<br>whole document; figures | 1-6, 9-11, 13-16 |
| A | US 2004195440 A1 (LIU PENGFEI [CA]) 07 October 2004 (07.10.2004)<br>whole document | 1-16 |
| A | US 5401196 A (TRIANTAFYLLOU MICHAEL S [US] et al.)<br>28 March 1995 (28.03.1995)<br>whole document | 1-16 |

☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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"&" document member of the same patent family

| Date of the actual completion of the international search | Date of mailing of the international search report |
|---|---|
| 06 October 2015 (06.10.2015) | 08 October 2015 (08.10.2015) |

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**INTERNATIONAL SEARCH REPORT**
**Information on Patent Family Members**

International application No.
PCT/FI2015/050507

| Patent document cited in search report | Publication date | Patent family members(s) | Publication date |
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**INTERNATIONAL SEARCH REPORT**

International application No.
PCT/FI2015/050507

CLASSIFICATION OF SUBJECT MATTER

IPC
***B63H 1/36*** (2006.01)
***B63H 5/03*** (2006.01)