(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) **EP 2 944 558 A1**

(12) # EUROPEAN PATENT APPLICATION

(43) Date of publication:
18.11.2015 Bulletin 2015/47

(51) Int Cl.:
B63H 1/36 *(2006.01)*

(21) Application number: **14168271.6**

(22) Date of filing: **14.05.2014**

(84) Designated Contracting States:
AL AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HR HU IE IS IT LI LT LU LV MC MK MT NL NO PL PT RO RS SE SI SK SM TR
Designated Extension States:
BA ME

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(54) **Oscillating foil propulsion system and method for controlling a motion of an oscillating movable foil**

(57) The invention relates to an oscillating foil propulsion system (1) comprising a movable foil (2), a pitch mechanism (5) connected to the movable foil (2) and configured to control a pitch motion of the foil (2), a heave mechanism (6) connected to the movable foil (2) and configured to control a heave motion of the foil (2), and wherein at least one of the pitch (5) and heave mechanisms (6) is configured to adjust an amplitude of the respective motion of the movable foil (2). The invention further relates to a method for controlling a motion of an oscillating movable foil (2) of a marine propulsion system (1).

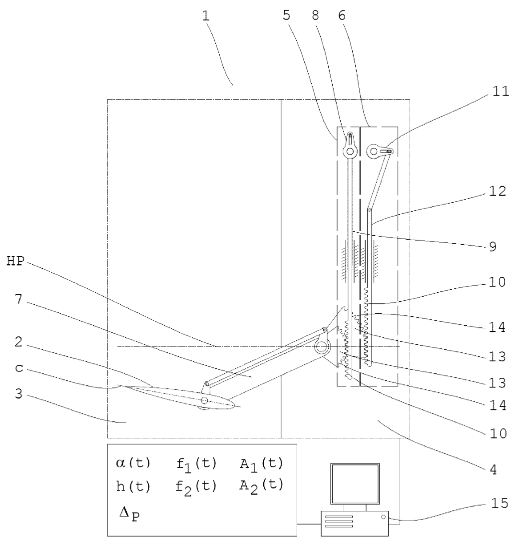

Fig. 2

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Description

TECHNICAL FIELD OF THE INVENTION:

[0001] The present invention relates to a marine propulsion system, in particular to an oscillating foil propulsion system. The present invention further relates to a method for controlling a motion of an oscillating movable foil of a marine propulsion system. 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] Many different marine propulsion devices for use in a fluid are known, by means of which a vessel can be propelled or propelled and steered. Typical propulsion systems include, for example, side paddle wheels, conventional screw propellers, podded propulsion devices, vertical axis propellers, sails, kite sails, or Flettner rotors.

[0003] Presently, vessels, especially cargo vessels, are usually equipped with at least one screw propeller for propulsion. The efficiency of the propeller is typically about 60 % - 70 %. 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 dolphins or whales swim. The efficiency of such sea animals has been estimated to be greater than 70 %. Theoretical fin propulsion has been widely studied in the past and new fin propulsion systems may, for example, lead to achievement of a greater propulsor efficiency compared to a conventional propeller.

[0004] The document US 2011/0255971 A1, which is considered to be the closest prior art, discloses an apparatus for oscillating a foil in a fluid. The apparatus comprises a first crank mechanism and a second crank mechanism connected to a foil. Said first crank mechanism and said second crank mechanism have different crank pin offsets, are functionally connected such that when driven the speed of revolution of said first crank mechanism is the same as the speed of revolution of said second crank mechanism, and are out of phase with each other.

[0005] The crankshaft of the first crank mechanism is rotatable about a first axis of rotation and having a first crank pin offset relative to said first axis of rotation. The crankshaft of the second crank mechanism is rotatable about a second axis of rotation and having a second crank pin offset relative to said second axis of rotation. The length of the first and second crankshaft is constant and not adjustable. Therefore, the apparatus according to document US 2011/0255971 A1 allows adjustment of the frequency of the sinusoidal like pitch and heave motion of the foil by adjusting the speed of revolution of the crank mechanisms, but does not allow controlled adjustment of the peak amplitude of the pitch and heave motion, for example, to adjust the angle of attack depending on the direction and velocity of the oncoming local fluid flow in the foil working area.

SUMMARY OF THE INVENTION:

[0006] It is an object of certain embodiments of the present invention to provide an oscillating foil propulsion system. It is a further object of certain embodiments of the present invention to provide a method for controlling a motion of an oscillating movable foil of a marine propulsion system.

[0007] According to certain embodiments, there is described a marine propulsion system by means of which a vessel can be propelled. According to certain embodiments, there is further described a propulsive device, which implements aspects of the movement of a fin of an animal, such as a whale or a dolphin, wherein the required motion of the propulsion system is controllable and adjustable.

[0008] These and other objects are achieved by the present invention, as hereinafter described and claimed. Thus the invention concerns an oscillating foil propulsion system comprising a movable foil, a pitch mechanism connected to the movable foil and configured to control a pitch motion of the foil, a heave mechanism connected to the movable foil and configured to control a heave motion of the foil, and wherein at least one of the pitch and heave mechanisms is configured to adjust an amplitude of the respective motion of the movable foil.

[0009] The pitch mechanism is configured to adjust a pitch angle of the pitch motion of the foil. The pitch mechanism is configured to cause the amplitude of the pitch motion to change from a first peak amplitude to a substantially different peak amplitude. The substantially different peak amplitude is preferably greater than or less than the first peak amplitude by 5-70 degrees, more preferably by 10-60 degrees. The pitch mechanism is preferably further configured to adjust a frequency of the pitch motion of the foil.

[0010] The heave mechanism is configured to adjust a heave of the heave motion of the foil. The heave mechanism is configured to cause the amplitude of the heave motion to change from a first peak amplitude to a substantially different peak amplitude. The heave mechanism is preferably further configured to adjust a frequency of the heave motion.

[0011] At least one of the pitch mechanism and the heave mechanism preferably includes a crank mechanism to control the amplitude of the pitch and/or heave motion. The crank mechanism preferably includes a crank arm, which is rotatable around an axis of rotation, and wherein the length of the crank arm is adjustable. Otherwise, the crank mechanism preferably includes a crank arm, which is rotatable around an axis of rotation, and a coupling which is movable along the crank arm. The coupling of the crank mechanism preferably includes a crank pin which is located at an adjustable distance from the axis of rotation. The pitch mechanism preferably includes a crank mechanism having a pitch rod. The pitch rod is then connected to a coupling of the pitch mechanism. The heave mechanism preferably includes a crank mechanism having a heave rod. The heave rod is then connected to a coupling of the heave mechanism. Otherwise, at least one of the pitch mechanism and the heave mechanism preferably includes hydraulic cylinders instead of a crank mechanism to control the amplitude of the pitch and/or heave motion. The amplitudes of the pitch and heave motion may be preferably also controlled by means of a rack and base module assembly, wherein the base module is linearly movable along the rack and at least one movable foil is connected to the base module.

[0012] The pitch mechanism preferably includes a pitch slider, which is connected to the pitch mechanism's crank mechanism, and wherein the pitch slider is linearly movable. The heave mechanism preferably includes a heave slider, which is connected to the heave mechanism's crank mechanism, and wherein the heave slider is linearly movable. At least one of the pitch mechanism and heave mechanism is preferably connected to the movable foil by a connector including at least one cam which includes pinions. The respective pitch or heave slider of said pitch mechanism and/or heave mechanism then includes rack pinions. The pinions of the cam are then coupled to said rack pinions. Otherwise, the pitch mechanism and the heave mechanism are preferably connected to the movable foil by at least one connector including a crank mechanism. The crank mechanism of the connector is then coupled to a pitch slider, a heave slider, and the movable foil.

[0013] At least a portion of the pitch mechanism and at least a portion of the heave mechanism are preferably configured to be housed within a hull of a vessel. The movable foil is configured to be outside of the hull of the vessel. Otherwise, the oscillating foil propulsion system is partially housed within a azimuthing housing. The connector extends then from outside the azimuthing housing to inside the housing.

[0014] The oscillating foil propulsion system is preferably further comprising a computer readable medium having stored thereon a set of computer implementable instructions capable of causing a processor, in connection with the pitch mechanism, to control a pitch angle of the movable foil, a frequency of the pitch motion, and an amplitude of the pitch motion. Additionally, the oscillating foil propulsion system is preferably further comprising a computer readable medium having stored thereon a set of computer implementable instructions capable of causing a processor, in connection with the heave mechanism, to control a heave of the movable foil, a frequency of the heave motion, and an amplitude of the heave motion.

[0015] The invention further concerns a method for controlling a motion of an oscillating movable foil of a marine propulsion system, comprising the steps of:

- varying an amplitude of a pitch motion of the movable foil to change from a first peak amplitude to a substantially different peak amplitude, and/or
- varying an amplitude of a heave motion of the movable foil to change from a first peak amplitude to a substantially different peak amplitude.

[0016] The method is preferably further comprising:

- receiving at least one input, said input selected from the group of: a speed of a vessel, a direction of a local fluid flow in relation to the movable foil, a velocity of a local fluid flow in relation to the movable foil, and a desired thrust of the vessel, and
- wherein at least one of the amplitude of the pitch motion and the amplitude of the heave motion is varied based on said at least one input.

[0017] The invention furthermore concerns 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 a movable foil and a heave mechanism capable of controlling a heave motion of the movable foil, to vary an amplitude of at least one of the pitch motion and the heave motion of the foil of an oscillating foil propulsion system.

[0018] The computer readable medium is preferably capable of causing the computing device to vary at least one of a pitch angle, a heave, a frequency of the pitch motion, a frequency of the heave motion, the amplitude of the pitch motion, and the amplitude of the heave motion depending on at least one of:

- a speed of a vessel,
- a direction of a local fluid flow in relation to the movable foil,
- a velocity of the local fluid flow in relation to the movable foil, and
- a desired thrust of the vessel.

[0019] Additionally, the invention concerns a computer program configured to cause a method in accordance with at least one of claims 16 - 17 to be performed.

[0020] Considerable advantages are obtained by means of the present invention. A vessel, for example a cargo vessel or a passenger vessel, can be propelled by means of the propulsion system according to the invention. The propulsion system implements aspects of the movement of an animal, such as a whale or a dolphin, and the required motion of the at least one foil is more natural, continuously controllable and adjustable by modification of parameters. Such parameters include the pitch angle, the heave, the frequency of the heave motion, the frequency of the pitch motion, the amplitude of the heave motion, the amplitude of the pitch motion, and the phase difference between pitch and heave. The motion of the foil can be optimized by means of controlled adjustment of the amplitude of the pitch motion and/or the amplitude of the heave motion of the foil, for example, depending on the speed of the vessel, the direction of a local fluid flow, the velocity of a local fluid flow and/or a desired thrust.

[0021] The present invention especially improves the propulsor efficiency of the foil over prior art. The efficiency improvement leads to reduced fuel consumption of the vessel and therefore to a longer maximum range as well as reduced emissions. Another advantage is the possibility to reduce the volume of the fuel tanks which increases the space for valuable payload on board. A combination of the aforementioned advantages, i.e. reduction of fuel consumption and reduction of fuel tank volume, is also possible.

[0022] Additionally, 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 propeller. The wetted propulsion surface of the at least one foil can be 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.

[0023] Furthermore, the propulsion system according to certain embodiments of the invention does not include any connecting rods which are arranged in vertical direction outside the vessel. In absence of vertical connecting rods the strength and stability of the propulsion system can be improved over prior art. Due to the orientation of the at least one connector, which is not arranged in an essentially vertical direction, impact forces in case of an collision of the connector with another object will be minimized. This reduces the risk of damaging the propulsion system or of a total system failure and therefore improves safety of a vessel during operation over prior art.

BRIEF DESCRIPTION OF THE DRAWINGS:

[0024] 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:

Fig. 1 illustrates a schematic view of a propulsion system according to a first embodiment of the invention,

Fig. 2 illustrates a schematic view of a propulsion system according to a second embodiment of the invention,

Fig. 3 illustrates a schematic view of a crank mechanism of a pitch or heave mechanism of a propulsion system according to a third embodiment of the invention,

Fig. 4 illustrates a schematic view of a propulsion system according to a fourth embodiment of the invention,

Fig. 5 illustrates a schematic view of a part of a vessel which is equipped with two propulsion systems according to a fifth embodiment of the invention,

Fig. 6 illustrates a schematic time-angle/vertical position-diagram of the pitch and heave motion of a propulsion system according to a sixth embodiment of the invention, wherein the amplitudes of the pitch motion and the heave motion are decreasing,

Fig. 7 illustrates a schematic time-angle/vertical position-diagram of the pitch and heave motion of a propulsion system according to a seventh embodiment of the invention, wherein the amplitudes of the heave motion are increasing,

Fig. 8 illustrates a schematic time-angle/vertical position-diagram of the pitch and heave motion of a propulsion system according to an eighth embodiment of the invention, wherein the amplitudes of the pitch motion are decreasing,

Fig. 9 illustrates a schematic time-angle/vertical position-diagram of the pitch and heave motion of a propulsion system according to a ninth embodiment of the invention, wherein the foil is high loaded, and

Fig. 10 illustrates a schematic time-angle/vertical position-diagram of the pitch and heave motion of a propulsion system according to a tenth embodiment of the invention, wherein the load of the foil is relatively small.

DETAILED DESCRIPTION OF EMBODIMENTS OF THE INVENTION:

[0025] In **Fig. 1** a schematic view of a propulsion system 1 according to a first embodiment of the invention is illustrated. The propulsion system 1 includes a movable foil 2 which is arranged in a fluid 3 outside a body 4. The system 1 further includes a pitch mechanism 5 for adjusting a pitch angle $\alpha(t)$ between the chord line c of the foil 2 and a horizontal plane HP, a frequency $f_1(t)$ of the pitch motion, and an amplitude $A_1(t)$ of the pitch motion of the movable foil 2. The system 1 also includes a heave mechanism 6 for adjusting a heave h(t) of the movable foil in vertical direction, a frequency $f_2(t)$ of the heave motion, and an amplitude $A_2(t)$ of the heave motion of the movable foil 2. The pitch and heave mechanisms 5, 6 are arranged inside the body 4. A connector 7 is extending from outside the body 4 to inside the body 4 and is connected to and adapted to interact with the pitch mechanism 5, the heave mechanism 6 and the movable foil 2. The movable foil may have a symmetrical or asymmetrical profile. The aspect ratio of the movable foil 2 is preferably greater than 2 or 3, even more preferably greater than 4 or 5 in order to provide advantageous lift coefficients of the movable foil 2. The movable foil 2 may further be equipped with so called end plates or winglets. The system 1 is adapted to modify at least one of the pitch angle $\alpha(t)$, the heave h(t), the frequency $f_1(t)$ of the pitch motion, the frequency $f_2(t)$ of the heave motion, the amplitude $A_1(t)$ of the pitch motion, the amplitude $A_2(t)$ of the heave motion, and a phase difference $\Delta_P(t)$ between pitch and heave. The maximum pitch angles $\alpha(t)$, i.e. the peak amplitudes $A_1(t)$ of the movable foil 2, are typically in the range between +70° and -70° from the horizontal plane HP. Other embodiments may include other maximum pitch angles $\alpha(t)$ of the at least one foil 2, for example +60° and -60°, +45° and -45°, +35° and -35°, or any other pitch angles $\alpha(t)$. Maximum positive and negative pitch angles $\alpha(t)$ of the foil 2 may be further equal or different. The maximum frequency $f_1(t)$ of the pitch motion and the maximum frequency $f_2(t)$ of the heave motion is typically less than 3 Hz.

[0026] In **Fig. 2** a schematic view of a propulsion system 1 according to a second embodiment of the invention is illustrated. The propulsion system 1 includes a movable foil 2, which is arranged in a fluid 3 outside a body 4. The system 1 further includes a pitch mechanism 5 for adjusting a pitch angle $\alpha(t)$, a frequency $f_1(t)$ of the pitch motion, and an amplitude $A_1(t)$ of the pitch motion of the movable foil 2 and a heave mechanism 6 for adjusting a heave h(t), a frequency $f_2(t)$ of the heave motion, and an amplitude A_2 (t) of the heave motion of the movable foil 2. The pitch and heave mechanisms 5, 6 are arranged inside the body 4. The pitch mechanism 5 includes a first crank mechanism 8, a movable pitch slider 9 which is connected to the first crank mechanism 8 on one side, and rack pinions 10 which are connected to, arranged on, or an integral part of the pitch slider 9. The heave mechanism 6 includes a second crank mechanism 11, a movable heave slider 12 which is connected to the second crank mechanism 11 on one side, and rack pinions 10 which are connected to, arranged on, or an integral part of the heave slider 12. A connector 7 is further extending from outside the body 4 to inside the body 4. The connector 7 includes two separate cams 13 inside the body 4, which each include pinions 14, which are coupled to and adapted to interact with the rack pinions 10 of the movable pitch slider 9 of the pitch mechanism 5 and the rack pinions 10 of the movable heave slider 12 of the heave mechanism 6, respectively. The connector 7 is outside the body 4 connected to and adapted to interact with the movable foil 2. The connector 7 for transmitting the heave motion may be hollow so that a mechanism for the adjustment of the pitch motion is arranged inside the connector 7. The system 1 is further comprising a computer readable medium having stored thereon a set of computer implementable instructions capable of causing a processor, in connection with the pitch mechanism and/or heave mechanism, to control the pitch angle $\alpha(t)$, the heave h(t), the frequency $f_1(t)$ of the heave motion, the frequency $f_2(t)$ of the pitch motion, the amplitude $A_1(t)$ of the heave motion, the amplitude $A_2(t)$ of the pitch motion, and the phase difference $\Delta_P(t)$ between pitch and heave. The system may further include sensors or measurement devices for measuring parameters, such as the pitch angle $\alpha(t)$, the heave h(t), the frequency $f_1(t)$ of the heave motion, the frequency $f_2(t)$ of the pitch motion, the amplitude $A_1(t)$ of the heave motion, the amplitude $A_2(t)$ of the pitch motion, or the velocity of the local fluid flow in the foil working area. The propulsion system 1 is especially suited for so called horizontally positioned foils.

[0027] In **Fig. 3** a schematic view of a crank mechanism 8, 11 of a pitch or heave mechanism 5, 6 of a propulsion system 1 according to a third embodiment of the invention is illustrated. At least one power source, which is not shown in Fig. 3, provides the first or second crank mechanism 8, 11 with rotational power which is transmitted to a rotating crank arm 16 which is rotatable about a first axis of rotation 17 or a fourth axis of rotation 23, respectively, and having a first crank pin 18 or a third crank pin 26, respectively, which is linearly movable in the longitudinal direction of the rotating crank arm 16. The first crank pin 18 represents the second axis of rotation 19 and the third crank pin 26 represents the fifth axis of rotation 24, respectively. A pitch rod 20 is rotatably connected at one end to said first crank pin 18 about the second axis of rotation 19 or a heave rod 30 is rotatably connected at one end to said third crank pin 26 about the fifth axis of rotation 24, respectively. A pitch slider 9 is connected at one end to a second crank pin 21 about the third axis of rotation 22 or a heave slider 12 is connected at one end to a fourth crank pin 27 about a sixth axis of rotation 25, respectively. Contrary to prior art, in addition to the rotation of the crank arm 16 about the first axis of rotation 17 or the fourth axis of rotation 23, the position of the first crank pin 18 or the third crank pin 26 can be linearly adjusted relative to the first axis of rotation 17 or the fourth axis of rotation 23 by an actuator. In other words, contrary to prior art, the rotating radius r(t) of the second axis of rotation 19 or the fifth axis of rotation 24 relative to the first axis of rotation 17 or the fourth axis of rotation 23 can be adjusted, i.e. the amplitude $A_1(t)$ of the pitch motion or the amplitude $A_2(t)$ of the heave motion can be controlled with the help of the crank mechanisms 8, 11. A small rotating radius r(t) of the second axis of rotation 17 equals a small amplitude $A_1(t)$ of the pitch motion and a small rotating radius r(t) of the fifth axis of rotation 24 equals a small amplitude $A_2(t)$ of the heave motion and vice versa. The frequency $f_1(t)$ of the pitch motion and the frequency $f_2(t)$ of the heave motion can be varied by adjusting the speed of revolution of the crank arm 16 of the crank mechanisms 8, 11.

[0028] In **Fig. 4** a schematic view of a propulsion system 1 according to a fourth embodiment of the invention is illustrated. The propulsion system 1 includes a movable foil 2, which is arranged in a fluid 3 outside a body 4. The system 1 further includes a pitch mechanism 5 for adjusting a pitch angle $\alpha(t)$, a frequency $f_1(t)$ of the pitch motion, and an amplitude $A_1(t)$ of the pitch motion of the foil 2 and a heave mechanism 6 for adjusting a heave h(t), a frequency $f_2(t)$ of the heave motion, and an amplitude $A_2(t)$ of the heave motion of the foil 2. The pitch and heave mechanisms 5, 6 are arranged inside the body 4 and each includes a crank mechanism 8, 11. The first crank mechanism 8 of the pitch mechanism 5 is providing the movement to the pitch motion and the second crank mechanism 11 of the heave mechanism 6 is providing the movement to the heave motion. A rotation of the second axis of rotation 19 about the first axis of rotation 17 of the pitch mechanism 5 together with a rotation of the fifth axis of rotation 24 about the fourth axis of rotation 23 of the heave mechanism 6 would result in a simultaneous pitch and heave motion of the foil 2. The crank mechanisms 8, 11 of the pitch and heave mechanisms 5, 6 are out of phase with each other. The phase angle of the pitch and heave motion is adjusted by the angle difference $\Delta_P(t)$ of the crank arms 16. The rotation of the crank arm 16 of the first crank mechanism 8 leads to a linear movement of the pitch slider 9 via the first crank pin 18, the pitch rod 20 and the second crank pin 21. The rotation of the crank arm 16 of the second crank mechanism 11 leads to a linear movement of the heave slider 12 via the third crank pin 26, the heave rod 30 and the fourth crank pin 27. Both sliders 9, 12 are supported by sliding bearings 28, 29. The pitch slider 9 is further rotatable connected to a lower pitch rod 31 about a seventh axis of rotation 32 via a fifth pin 33 and the heave slider 12 is rotatable connected to a lower heave rod 34 about an eighth axis of rotation 35 via a sixth pin 36. Additionally, a connector 7 is extending from outside the body 4 to inside the body 4. The connector 7 includes a third crank mechanism and is connected to and adapted to interact with the lower pitch rod 31 of the pitch mechanism 5 via a pitch lever 37, with the lower heave rod 34 of the heave mechanism 6 via a heave lever 46 and with the foil 2 via the hydrofoil crank 47. The pitch lever 37 of the third crank mechanism is rotatable connected to one end of the lower pitch rod 31 about a ninth axis of rotation 38 via a seventh pin 39 and rotatable connected to one end of a pitch crank 40 about a tenth axis of rotation 41 via an eighth pin 42. The pitch crank 40 of the third crank mechanism is further rotatable connected to a heave connecting rod 43 about an eleventh axis of rotation 44 via an ninth pin 45. The heave connecting rod 43 is rotatable connected to a heave crank 48 about a twelfth axis of rotation 49 via a tenth pin 50. The heave crank 48 is rotatable connected to the connecting rod 7 about a thirteenth axis of rotation 51 via an eleventh pin 52. The third crank mechanism also includes the heave lever 46, which is rotatable connected via the eleventh pin 52 to the connecting rod 7. The other side of the heave lever 46 is rotatable connected to the lower heave rod 34 about a fourteenth axis 53 of rotation via a twelfth pin 54. Additionally, the heave crank 48 is also rotatable connected via the tenth pin 50 to a hydrofoil connecting rod 55. The hydrofoil connecting rod 55 is rotatable connected to the hydrofoil crank 47 about a fifteenth axis of rotation 56 via a thirteenth pin 57. The hydrofoil crank 47 is then rotatable connected to the foil 2 about a sixteenth axis of rotation 58 via a fourteenth pin 59. The propulsion system 1 is especially suited for so called horizontally positioned foils.

[0029] According to other embodiments of the invention the pitch mechanism 5 may include two or more hydraulic cylinders instead of the crank mechanism 8. The heave mechanism 6 may also include two or more hydraulic cylinders instead of the crank mechanism 11. The hydraulic cylinders are configured to control the pitch angle $\alpha(t)$, the frequency $f_1(t)$ of the pitch motion, and the amplitude $A_1(t)$ of the pitch motion and/or the heave h(t), the frequency $f_2(t)$ of the heave motion, and the amplitude $A_2(t)$ of the heave motion. According to further embodiments of the invention at least one rack may be fixedly attached to the stern of a hull 61 of a vessel 60. A base module, which is movable in vertical direction along the rack and configured to control the heave h(t), the frequency $f_2(t)$ of the heave motion, and the amplitude $A_2(t)$ of the heave motion of the movable foil 2, is then connected to the rack. In this case at least one movable foil 2 is further connected to the base module. Preferably, one movable foil 2 is connected on the starboard side and one movable foil 2 is connected on the port side of the movable base module. The movable base module may preferably include the pitch mechanism 5 which is configured to control the pitch angle $\alpha(t)$, the frequency $f_1(t)$ of the pitch motion, and the amplitude A_1 (t) of the pitch motion of the movable foil 2. According to another embodiment of the invention the pitch mechanism and the heave mechanism may, for example, also include connecting rods which are arranged in an essentially vertical direction and connected to the crank mechanisms or the hydraulic cylinders at one end as well as to the movable foil 2 at the other end. The connecting rods then extend from outside the vessel 60 to inside the hull 61 of the vessel 60 and transmit the required motion to the movable foil 2. The connecting rods may be preferably arranged in a streamlined enclosure to reduce the resistance of the propulsion system 1.

[0030] In **Fig. 5** a schematic view of a part of a vessel 60 which is equipped with two propulsion systems 1 according to a fifth embodiment of the invention is illustrated. The propulsion systems 1 each include two movable foils 2 which are arranged in a fluid 3 outside the vessel 60. The pitch and heave mechanisms 5, 6 of the foils 2, which are not shown in Fig. 4, are arranged inside the body 4. Connectors 7 are extending from outside the body 4 to inside the body 4 and are each connected to the pitch mechanism 5, to the heave mechanism 6 and to the foils 2. Only one seal is required for each connector 7 at the position where the connector 7 extends from outside the hull 61 to inside the hull 61. The two propulsion systems 1 may be controlled by one or more computing devices 15 with an implemented computer aided algorithm stored thereon. The local fluid flow in transversal direction in the foil working area is in particular depending on the service speed, the hullform, and the form of the connector 7 of the vessel 60. According to other embodiments of the invention the pitch and heave mechanism 5, 6 may be arranged inside a submerged azimuthing housing, which is connected to a steering module, which is to be installed in the hull 61 of the vessel 60. With the help of such a propulsion system 1 it would be possible to direct the desired thrust into any direction. In other words, such a propulsion system 1 which can rotate in an essentially horizontal plane around 360° can be also used for steering a vessel 60.

[0031] In **Fig. 6** a time-angle/vertical position-diagram of the pitch and heave motion of a propulsion system according to a sixth embodiment of the invention is illustrated. The diagram represents an acceleration of a vessel from zero speed up to a desired service speed. The peak amplitudes $A_1(t)$ of the pitch motion and the peak amplitudes $A_2(t)$ of the heave motion are continuously or step-wise decreased after starting until the desired service speed of the vessel is reached. The system is configured to cause the pitch angle $\alpha(t)$ and the heave h(t) to change its range of oscillation from a first range to a second range. When starting, especially large heave amplitudes $A_1(t)$ are necessary to create a local fluid flow in the foil working area. With increasing service speed of the vessel the oncoming local fluid flow in the foil working area is changing from a rather vertical direction to a more horizontal direction and therefore continuous or step-wise reduction of the peak amplitudes $A_1(t)$ of the pitch motion is advantageous in order to provide sufficient angles of attack. When reaching the desired service speed, the at least one foil is controlled such that the peak amplitudes $A_1(t)$ of the sinusoidal like pitch angle function $\alpha(t)$ and the peak amplitudes $A_2(t)$ of the sinusoidal like heave function h(t) are constant. Contrary to prior art, the effect of the change of the direction and velocity of the local fluid flow in the foil working area on the angle of attack during acceleration of the vessel can be considered which leads to a thrust and efficiency improvement of the propulsion system. The peak amplitudes A_1 (t) of the pitch motion and the peak amplitudes A_2 (t) of the heave motion are preferably continuously controlled such that an optimum thrust is achieved and the maximum angle of attack is less than a critical angle of attack in order to avoid stalling of the movable foil. In Fig. 6 the peak amplitudes $A_1(t)$ of the pitch motion and the peak amplitudes $A_2(t)$ of the heave motion are continuously controlled depending on the speed of the vessel.

[0032] In **Fig. 7** a time-angle/vertical position-diagram of the pitch and heave motion of a propulsion system according to a seventh embodiment of the invention is illustrated, wherein the peak amplitudes A_2 (t) of the heave motion are increasing. While the peak amplitudes $A_1(t)$ of the pitch motion are constant during operation of the propulsion system, the peak amplitudes A_2 (t) of the heave motion are increased to increase the area load of the at least one foil. The system is configured to cause the heave h(t) to change its range of oscillation from a first range to a second range. The first range may, for example, comprise a heave between +0.5m and -0.5m and the second range may, for example, comprise a heave between +0.8m and -0.8m, between +1.2m and -1.2m, or any other heave range. In Fig. 7 the peak amplitudes $A_2(t)$ of the heave motion are controlled depending on a temporarily desired thrust.

[0033] In **Fig. 8** a time-angle/vertical position-diagram of the pitch and heave motion of a propulsion system according to an eighth embodiment of the invention is illustrated, wherein the peak amplitudes $A_1(t)$ of the pitch motion are decreasing. While the peak amplitudes $A_2(t)$ of the heave motion are constant during operation of the propulsion system, the peak amplitudes $A_1(t)$ of the pitch motion are decreased in order to optimize the angle of attack of the at least one foil of the propulsion system. The system is configured to cause the pitch angle $\alpha(t)$ to change its range of oscillation from a first range to a second range. The first range may, for example, comprise angles between +70° and -70° and the second range may, for example, comprise angles between +30° and -30°, or any other angles. In Fig. 8 the peak amplitudes $A_1(t)$ of the pitch motion are continuously controlled depending on the direction and velocity of a local fluid flow in the foil working area.

[0034] In **Fig. 9** a time-angle/vertical position-diagram of the pitch and heave motion of a propulsion system according to a ninth embodiment of the invention is illustrated, wherein the movable foil is high loaded. The peak amplitudes $A_2(t)$ of the heave motion are constant during operation and at the system's maximum. The peak amplitudes $A_1(t)$ of the pitch motion are also constant during operation, but not at the system's maximum in order to provide sufficient angles of attack.

[0035] In **Fig. 10** a time-angle/vertical position-diagram of the pitch and heave motion of a propulsion system according to a tenth embodiment of the invention is illustrated, wherein the area load of the movable foil is relatively small. The peak amplitudes $A_1(t)$, $A_2(t)$ of the pitch motion and the heave motion are constant during operation and not at the system's maximum. Increasing the heave h(t) would increase the area load of the foil. The peak amplitude $A_1(t)$ of the pitch motion is depending on the direction and velocity of the oncoming local fluid flow in the foil working area. Smaller angles of attack would reduce the area load further.

[0036] 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.

[0037] 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.

[0038] The pitch angle $\alpha(t)$, the heave h(t), the frequency $f_1(t)$ of the pitch motion, the frequency $f_2(t)$ of the heave motion, the amplitude $A_1(t)$ of the pitch motion, the amplitude $A_2(t)$ of the heave motion, the phase difference $\Delta_P(t)$ between pitch and heave, and the distance r(t) are functions of time.

[0039] 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 described above.

List of reference numbers:

[0040]

1	propulsion system
2	foil
3	fluid
4	body
5	pitch mechanism
6	heave mechanism
7	connector
8	first crank mechanism
9	pitch slider
10	rack pinions
11	second crank mechanism
12	heave slider
13	cam
14	pinions
15	computing device
16	crank arm
17	first axis of rotation
18	first crank pin
19	second axis of rotation
20	pitch rod
21	second crank pin
22	third axis of rotation
23	fourth axis of rotation
24	fifth axis of rotation
25	sixth axis of rotation
26	third crank pin
27	fourth crank pin
28	sliding bearing
29	sliding bearing
30	heave rod
31	lower pitch rod
32	seventh axis of rotation
33	fifth pin
34	lower heave rod
35	eighth axis of rotation
36	sixth pin
37	pitch lever
38	ninth axis of rotation
39	seventh pin
40	pitch crank
41	tenth axis of rotation
42	eighth pin
43	heave connecting rod
44	eleventh axis of rotation
45	ninth pin
46	heave lever
47	hydrofoil crank
48	heave crank
49	twelfth axis of rotation
50	tenth pin
51	thirteenth axis of rotation
52	eleventh pin
53	fourteenth axis of rotation
54	twelfth pin
55	hydrofoil connecting rod
56	fifteenth axis of rotation
57	thirteenth pin
58	sixteenth axis of rotation
59	fourteenth pin
60	vessel
61	hull
$A_1(t)$	amplitude of pitch motion
$A_2(t)$	amplitude of heave motion
c	chord line
$f_1(t)$	frequency of pitch motion
$f_2(t)$	frequency of heave motion
h(t)	heave
HP	horizontal plane
r(t)	rotating radius
t	time
$\alpha(t)$	pitch angle
$\Delta_P(t)$	phase difference

Claims

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

- a movable foil (2),
- a pitch mechanism (5) connected to the mov-

able foil (2) and configured to control a pitch motion of the foil (2),
- a heave mechanism (6) connected to the movable foil (2) and configured to control a heave motion of the foil (2), and
- wherein at least one of the pitch and heave mechanisms (5, 6) is configured to adjust an amplitude (A_1(t), A_2(t)) of the respective motion of the movable foil (2).

2. The oscillating foil propulsion system (1) according to claim 1, wherein the pitch mechanism (5) is configured to adjust a pitch angle (α(t)) of the pitch motion of the foil (2).

3. The oscillating foil propulsion system (1) according to either claim 1 or 2, wherein the pitch mechanism (5) is configured to cause the amplitude (A_1(t)) of the pitch motion to change from a first peak amplitude (A_1(t)) to a substantially different peak amplitude.

4. The oscillating foil propulsion system (1) according to claim 3, wherein the substantially different peak amplitude is greater than or less than the first peak amplitude (A_1(t)) by 5-70 degrees, preferably by 10-60 degrees.

5. The oscillating foil propulsion system (1) according to any of claims 1 to 4, wherein the pitch mechanism (5) is further configured to adjust a frequency (f_1(t)) of the pitch motion of the foil (2).

6. The oscillating foil propulsion system (1) according to any of claims 1 to 5, wherein the heave mechanism (6) is configured to adjust a heave (h(t)) of the heave motion of the foil (2).

7. The oscillating foil propulsion system (1) according to claim 6, wherein the heave mechanism (6) is configured to cause the amplitude A_2(t) of the heave motion to change from a first peak amplitude A_2(t) to a substantially different peak amplitude A_2(t).

8. The oscillating foil propulsion system (1) according to any of claims 1 to 7, wherein the heave mechanism (6) is further configured to adjust a frequency (f_2(t)) of the heave motion.

9. The oscillating foil propulsion system (1) according to any one of claims 1 to 8, wherein at least one of the pitch mechanism (5) and the heave mechanism (6) includes a crank mechanism (8, 11).

10. The oscillating foil propulsion system (1) according to claim 9, wherein the crank mechanism (8, 11) includes a crank arm (16), which is rotatable around an axis of rotation (17, 23), and wherein the length of the crank arm is adjustable or the crank arm (16) includes a coupling which is movable along the crank arm (16).

11. The oscillating foil propulsion system (1) according to any one of claims 1 to 10, wherein at least one of the pitch mechanism (5) and the heave mechanism (6) includes hydraulic cylinders and/or the heave mechanism (5) includes a rack and a movable base module.

12. The oscillating foil propulsion system (1) according to any one of claims 1 to 11, wherein at least a portion of the pitch mechanism (5) and at least a portion of the heave mechanism (6) are configured to be housed within a hull (61) of a vessel (60) and wherein the movable foil (2) is configured to be outside of the hull (61) of the vessel (60).

13. The oscillating foil propulsion system (1) according to any one of claims 1 to 11, wherein the oscillating foil propulsion system (1) is partially housed within a azimuthing housing, and wherein a connector (7) extends from outside the azimuthing housing to inside the housing and wherein the movable foil (2) is configured to be outside of the azimuthing housing.

14. The oscillating foil propulsion system (1) according to any one of claims 1-13 further comprising a computer readable medium having stored thereon a set of computer implementable instructions capable of causing a processor, in connection with the pitch mechanism (5), to control a pitch angle (α(t)) of the movable foil, a frequency (f_2(t)) of the pitch motion, and an amplitude (A_1(t)) of the pitch motion.

15. The oscillating foil propulsion system (1) according to any one of claims 1-14 further comprising a computer readable medium having stored thereon a set of computer implementable instructions capable of causing a processor, in connection with the heave mechanism (6), to control a heave (h(t)) of the movable foil, a frequency (f_1(t)) of the heave motion, and an amplitude (A_2(t)) of the heave motion.

16. A method for controlling a motion of an oscillating movable foil (2) of a marine propulsion system (1), comprising the steps of:

- varying an amplitude (A_1(t)) of a pitch motion of the movable foil (2) to change from a first peak amplitude to a substantially different peak amplitude, and/or
- varying an amplitude (A_2(t)) of a heave motion of the movable foil (2) to change from a first peak amplitude to a substantially different peak amplitude.

17. The method according to claim 16, further comprising:

- receiving at least one input, said input selected from the group of: a speed of a vessel (60), a direction of a local fluid flow in relation to the movable foil (2), a velocity of a local fluid flow in relation to the movable foil (2), and a desired thrust of the vessel (60), and
- wherein at least one of the amplitude ($A_1(t)$) of the pitch motion and the amplitude ($A_2(t)$) of the heave motion is varied based on said at least one input.

18. A computer readable medium having stored thereon a set of computer implementable instructions capable of causing a computing device (15), in connection with a pitch mechanism (5) capable of controlling a pitch motion of a movable foil (2) and a heave mechanism (6) capable of controlling a heave motion of the movable foil (2), to vary an amplitude ($A_1(t)$, $A_2(t)$) of at least one of the pitch motion and the heave motion of the foil (2) of an oscillating foil propulsion system (1).

19. The computer readable medium according to claim 18 capable of causing the computing device (15) to vary at least one of a pitch angle ($\alpha(t)$), a heave ($h(t)$), a frequency ($f_1(t)$) of the pitch motion, a frequency ($f_2(t)$) of the heave motion, the amplitude ($A_1(t)$) of the pitch motion, and the amplitude ($A_2(t)$) of the heave motion depending on at least one of:

- a speed of a vessel (60),
- a direction of a local fluid flow in relation to the movable foil (2),
- a velocity of the local fluid flow in relation to the movable foil (2), and
- a desired thrust of the vessel (60).

20. A computer program configured to cause a method in accordance with at least one of claims 16 - 17 to be performed.

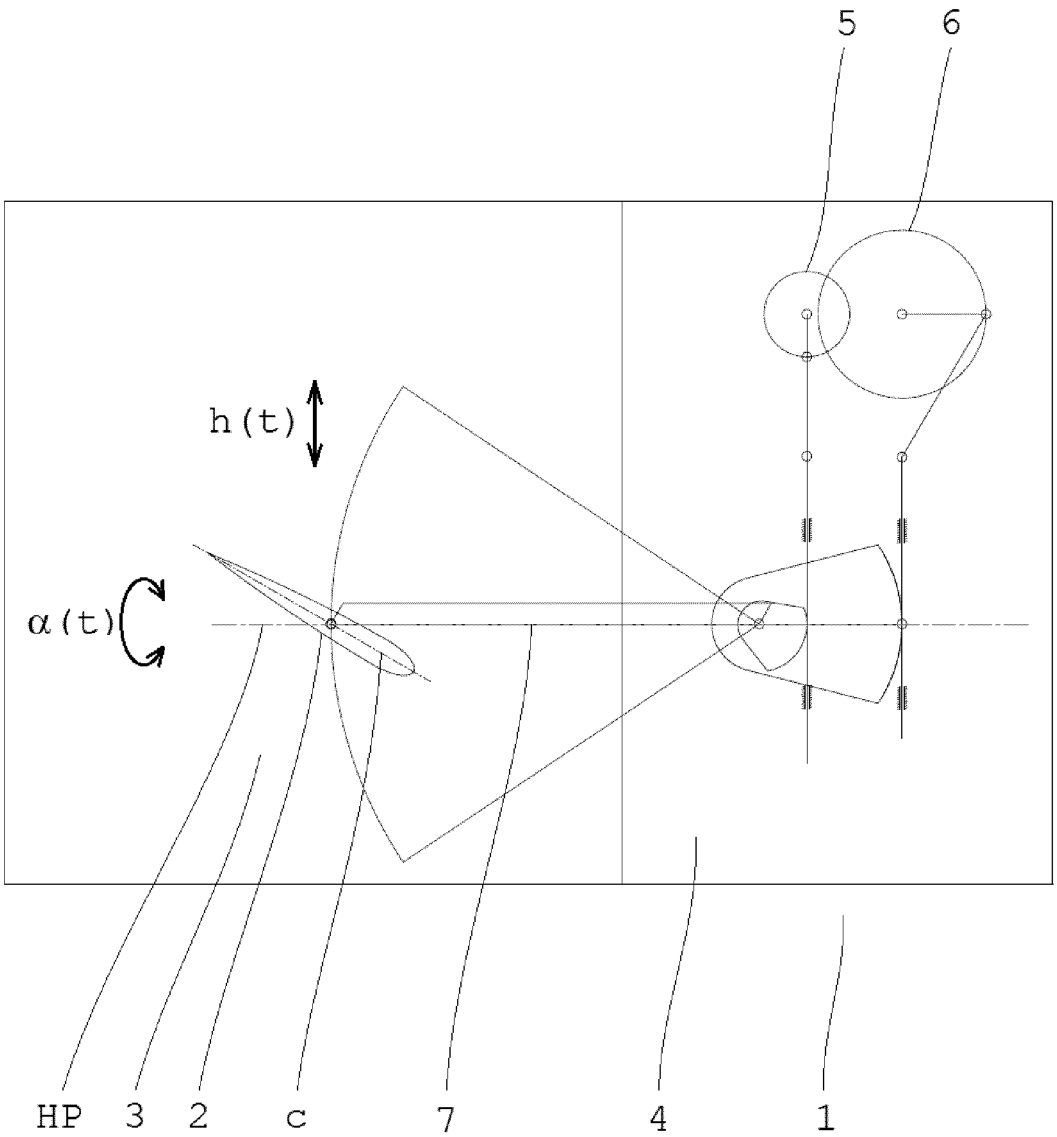

Fig. 1

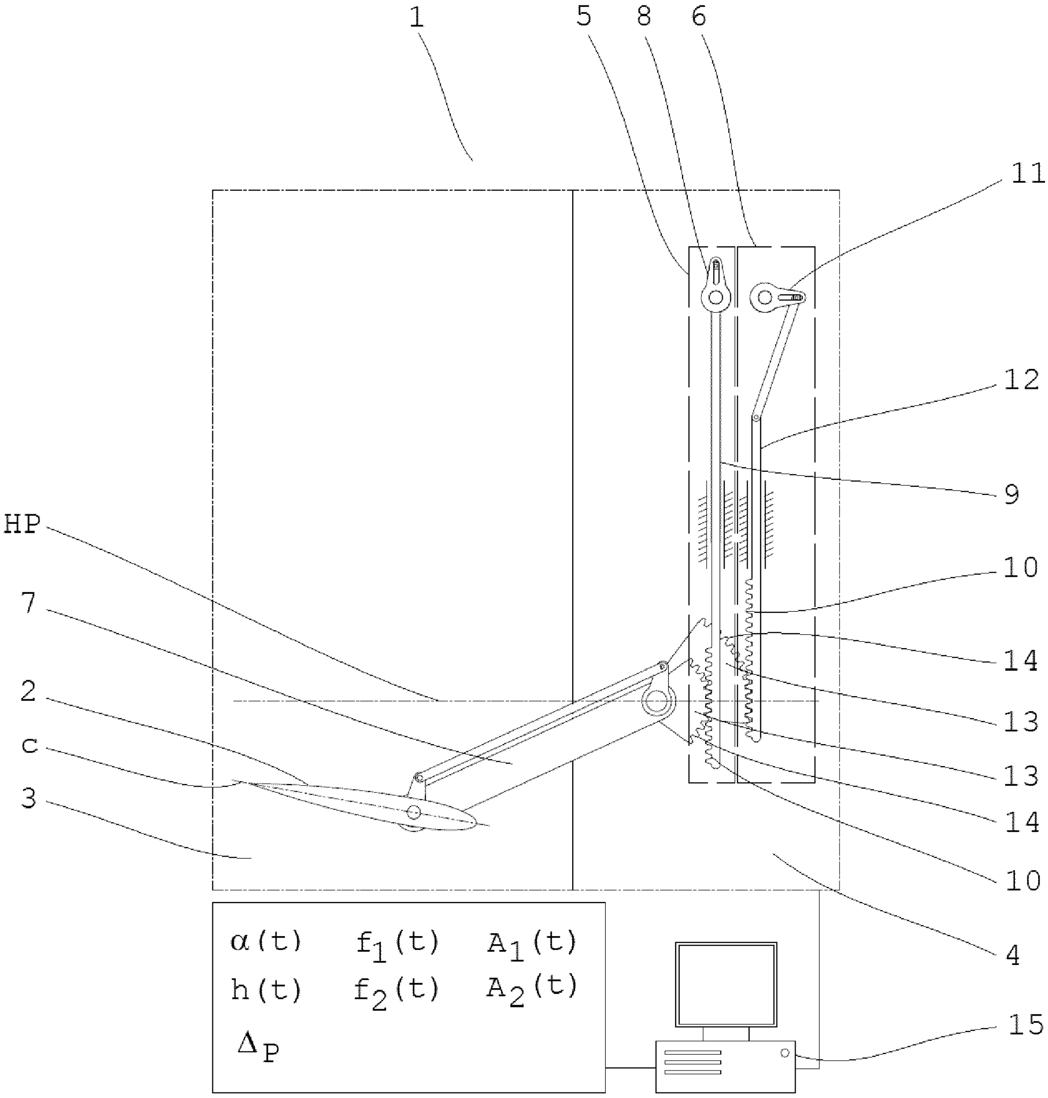

Fig. 2

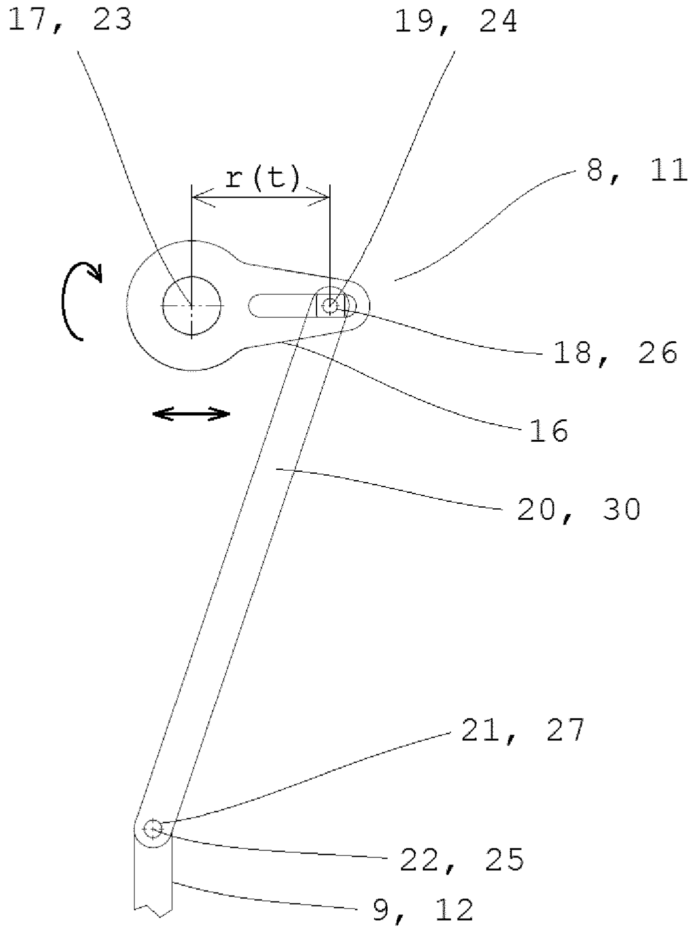

Fig. 3

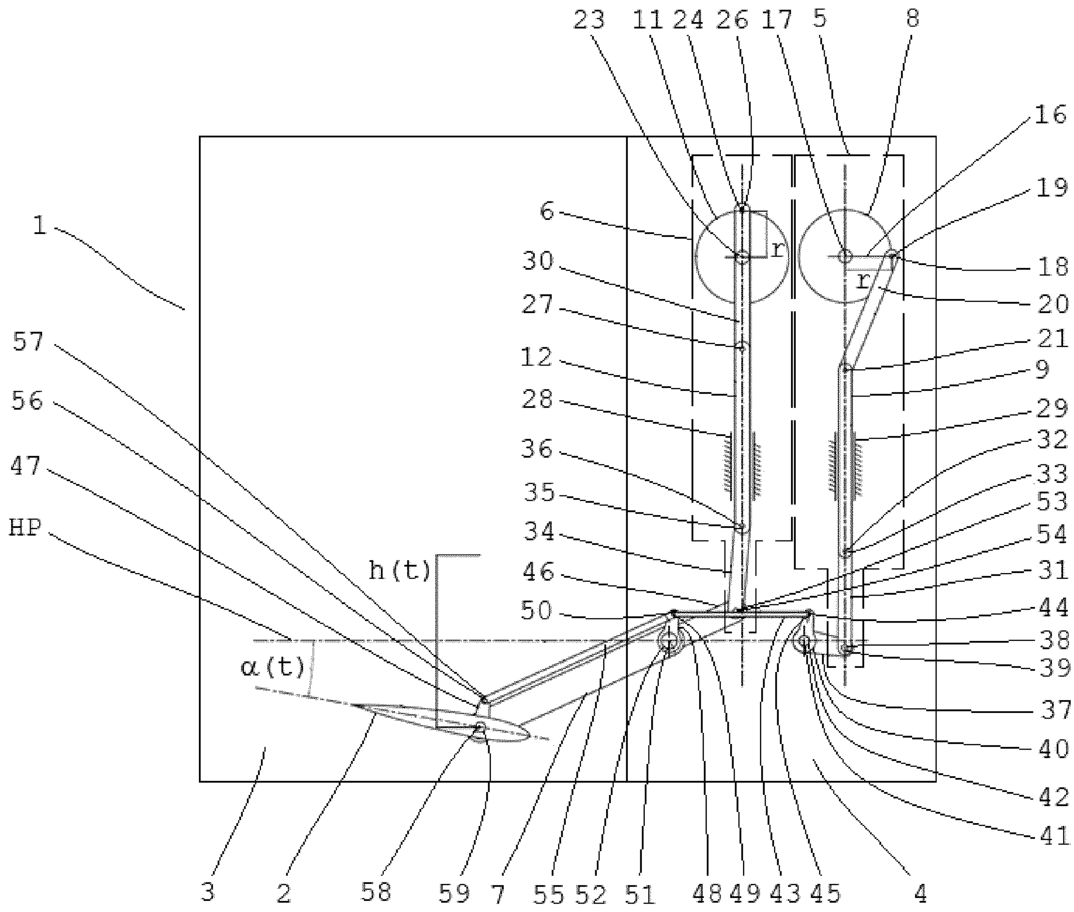
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Fig. 4

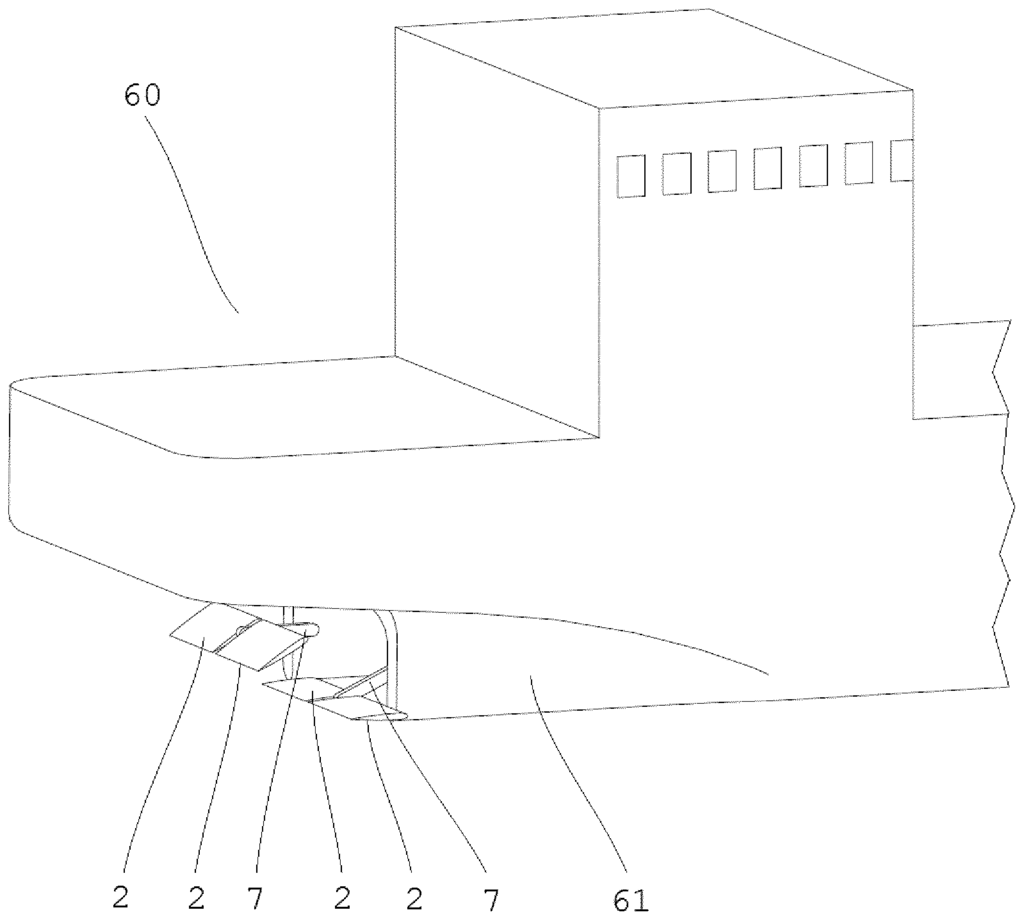

Fig. 5

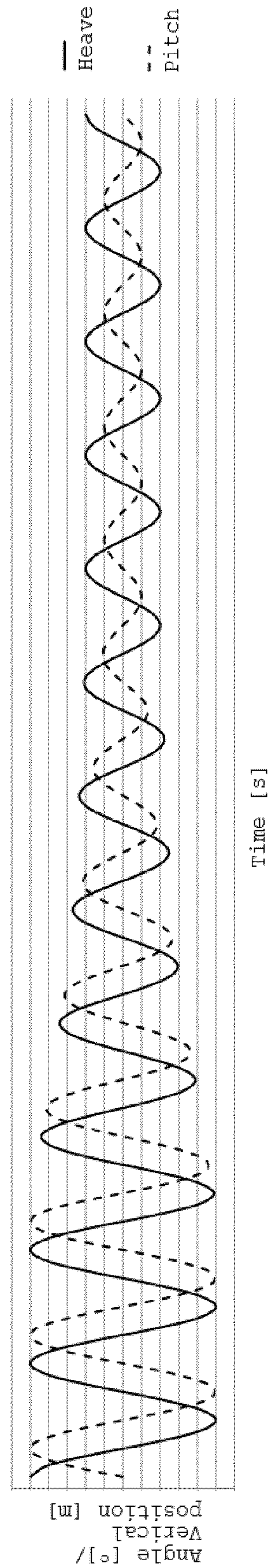

Fig. 6

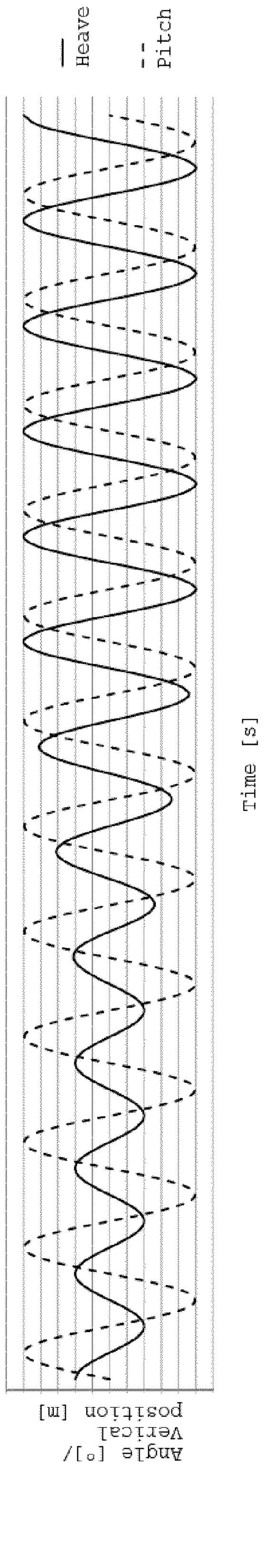

Fig. 7

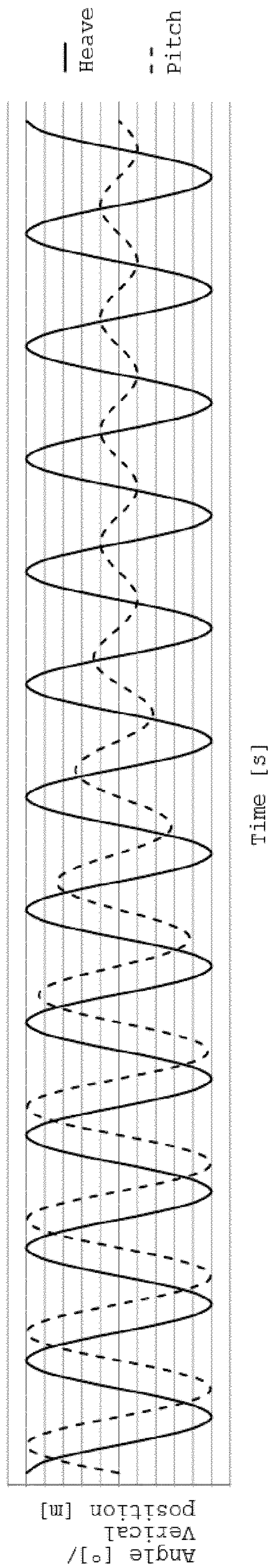

Fig. 8

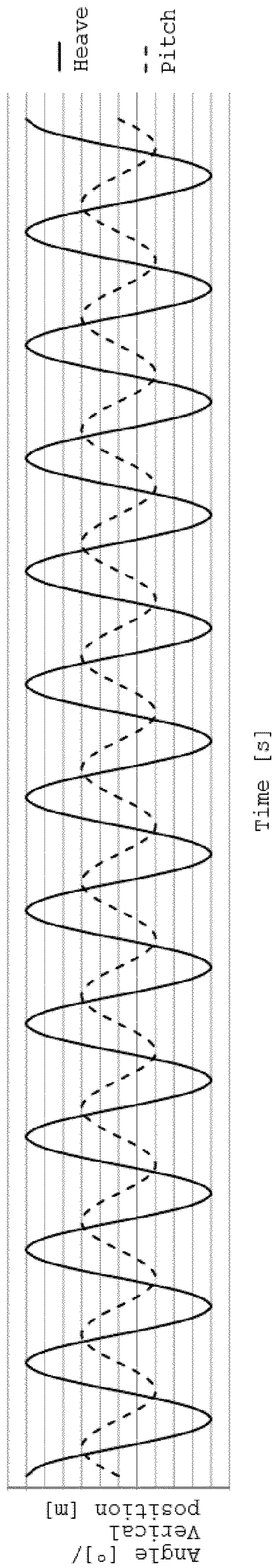

Fig. 9

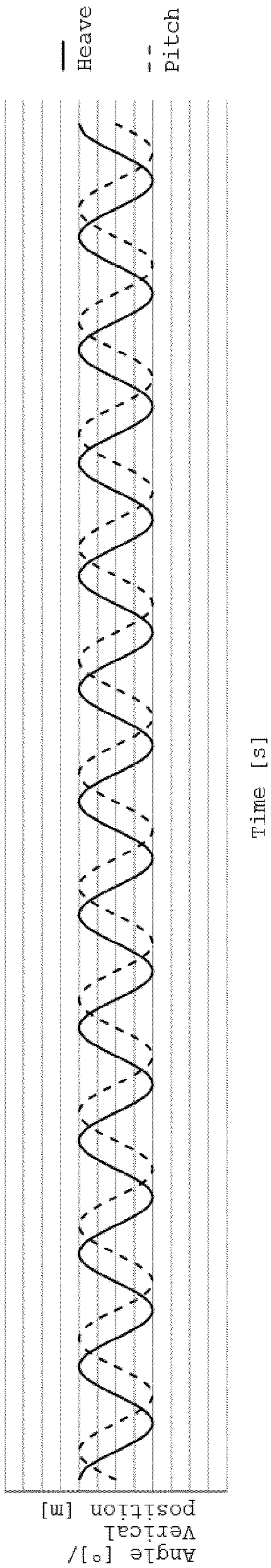

Fig. 10

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EUROPEAN SEARCH REPORT

Application Number
EP 14 16 8271

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Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X	YONGHUI HU YONGHUI HU ET AL: "Development and control of dolphin-like underwater vehicle", 2013 AMERICAN CONTROL CONFERENCE, 13 June 2008 (2008-06-13), pages 2858-2863, XP055151631, ISSN: 0743-1619, DOI: 10.1109/ACC.2008.4586927 ISBN: 978-1-47-990177-7	1-12, 14-19	INV. B63H1/36
A	* columns 1,2,4-8, * * figures 3-7 *	13	
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Y	* page 1, lines 10-14 * * page 4, line 7 - page 5, line 5 * * page 15, line 19 - page 17, line 13 * * page 20, line 22 - page 21, line 8 * * page 21, line 30 - page 22, line 7 * * page 23, lines 24-29 * * figures 1-9 *	13	
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A	* paragraph [0033] * * figure 5a *	1,16,18, 20	

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B63H

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
The Hague	12 November 2014	Blazquez Lainez, R

CATEGORY OF CITED DOCUMENTS

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12-11-2014

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For more details about this annex : see Official Journal of the European Patent Office, No. 12/82

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