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(54) Title: OSCILLATING HYDROFOIL, TURBINE, PROPULSIVE SYSTEM AND METHOD FOR TRANSMITTING ENERGY

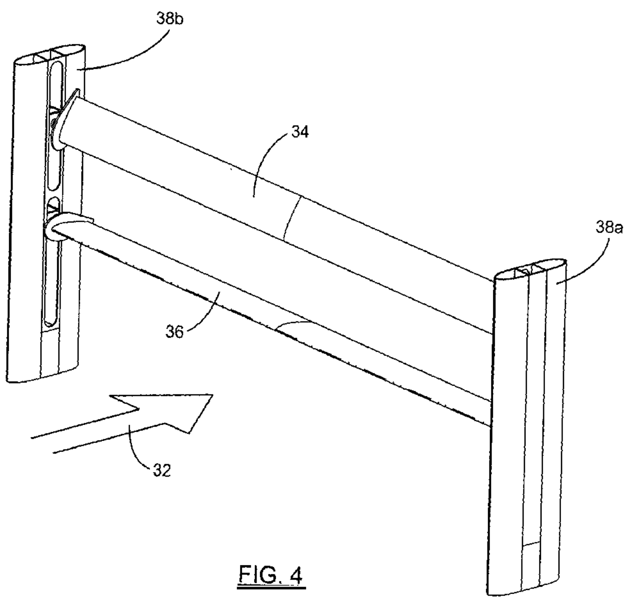

FIG. 4

(57) Abstract: System and method for converting kinetic energy from a fluid flow into mechanical energy, the method comprising the steps of: a) providing a turbine including first and second hydrofoils, each of the hydrofoils being able to move linearly in a heaving motion, and being able to oscillate about a spanwise axis in a pitching motion, said heaving and pitching motions being quasi-sinusoidal, b) coupling the heaving motions of the first and second hydrofoils to the pitching motions of the second and first hydrofoils respectively, with the pitch-heave motion phase being substantially equal to the inter-hydrofoil phase, the heaving motion of one of the hydrofoils thereby driving the pitching motion of the other hydrofoil; and c) transforming the heaving motions of the hydrofoils into a rotational movement of a rotatable shaft, with linear-to-rotary transmission means.

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OSCILLATING HYDROFOIL, TURBINE, PROPULSIVE SYSTEM AND METHOD FOR TRANSMITTING ENERGY

FIELD OF THE INVENTION

The present invention relates to the field of turbines and more specifically concerns turbines with oscillating foils.

BACKGROUND OF THE INVENTION

The prospect of harvesting water flow energy with hydrokinetic turbines is becoming more attractive than ever among renewable forms of energy, due to the high energy density of flowing water, to its predictability with both tidal and river applications, and the minimal environmental and human impact.

Known to the Applicant are the following publications and patent documents:

[1] The European Marine Energy Centre Ltd (EMEC), (2010): http://www.emec.org.uk/tidal_devices.asp

[2] Bernitsas, M., Raghavan, K., Ben-Simon, Y., and E.M.H., G., (2008). VIVACE (Vortex Induced Vibration Aquatic Clean Energy): A new concept in the generation of clean and renewable energy from fluid flow. ASME Journal of Offshore Mechanics and Arctic Engineering, 130(4), November, p. 041101.

[3] Bernitsas, M., Ben-Simon, Y., Raghavan, K., and E.M.H., G., (2009). The VIVACE Converter: Model tests at high damping and Reynolds number around 105. ASME Journal of Offshore Mechanics and Arctic Engineering, 131(1), February, p. 011102.

[4] Jones, K., Lindsey, K., and Platzer, M. (2003). An investigation of the fluid-structure interaction in an oscillating wing micro-hydropower generator. Fluid Structure Interaction II, Chakrabarti, Brebbia, Almorza, and Gonzalez-Palma, eds. WIT Press, Southampton, UK, pp. 73-82.

[5] Kinsey, T. and Dumas, G. (2010). Testing and Analysis of an Oscillating Hydrofoils Turbine Concept. ASME 2010 3rd Joint US-European Fluids Engineering Summer Meeting, Paper FEDSMICNMM201 0-30869, Montreal, Canada

[6] Kinsey, T. and Dumas, G. (2008). Parametric Study of an Oscillating Airfoil in a Power-Extraction Regime. AIAA Journal , 46 (6), pp. 1318-1330

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[13] Dumas, G. (2010). HAO-Laval: Le projet d'hydrolienne à ailes oscillantes. Journal de l'AQME, septembre 2010, Vol.25 (3), pp. 8-10.

[14] Kinsey, T., Dumas, G., Lalande, G., Ruel, J., Mehut, A., Viarouge, P., Lemay, J. and Jean, Y. (2011). Prototype Testing of a Hydrokinetic Turbine Based on Oscillating Hydrofoils. Renewable Energy, 36 (6), pp. 1710-1718.

Also known to the Applicant are these related patents:

US 7,493,759 B2 2/2009 Bernitsas et al. (VIVACE); WO 2004110859A1 6/2004 Lambert-Bolduc (Éolo); WO 2005108781A1 5/2005 Paish (Pulse Tidal); US 20060275109 A1 12/2006 Paish (Pulse Tidal); WO 2008053167A1 5/2008 Paish (Pulse Tidal); WO 2010015821A2 2/2010 Paish (Pulse Tidal); WO 2008144938A1 5/2008 Dumas et al. (U. Laval); US 6,273,680 B1 8/2001 Arnold; and US 6,323,563 B1 11/2001 Kallenberg.

Referring to FIG.1, the use of oscillating rectangular lifting surfaces 10a, 10b, referred to as hydrofoils, where the pitching and heaving motions of the hydrofoils are perpendicular to the flow, is advantageous and has been shown to be as efficient as rotating blades turbines, especially when compared to horizontal axis rotor blades 12, such as the ones used in most modern wind turbines.

When submitted to a fluid flow, an oscillating foil undergoes a combined sinusoidal, or quasi-sinusoidal, heave-pitch motion. It is known that the efficiency of a turbine is improved when the heaving, or translational, motion is leading the pitching, or angular motion.

With reference to FIGs. 2A to 2C, an implementation of a hydrokinetic turbine 14 based on oscillating hydrofoils 10 is shown. The cyclical heaving motion of a pair of tandem foils 10 is transformed and transmitted to a rotating shaft 16, using long aluminum rods 18a connected to crankshafts 20a. The pitching motion of the foils 10 is coupled to their heaving motion into a one degree-of-freedom system by the use of chains and sprockets driven by an additional set of rods 18b and crankshafts 20b connected to the rotating shaft 16.

Although functional, this implementation has some drawbacks. One of them comes from the use of the elongated rods 18a, 18b oscillating into the flowing water which causes a loss of energy. Another drawback is that the hydrodynamic forces on the rods generate vibrations which contribute to premature wear of the bearings. Also, the phase difference between the oscillating motions of both hydrofoils is 180°. This means that they reach their zero-production points, at top and bottom positions, at the same time, which results in an undesirable fluctuating power output.

There is therefore a need to transmit energy from a fluid flow with increased efficiency. It would also be desirable to provide a transmission system or method which limits mechanical losses, improves robustness and resistance to wear, and evens out the output power curve.

SUMMARY OF THE INVENTION

An object of the present invention is to provide a turbine, a propulsive system, a method or a hydrofoil addressing at least one of the above-mentioned needs.

According to a first aspect of the invention, a turbine is provided. The turbine is for converting kinetic energy from a fluid flow into mechanical energy by driving a rotatable shaft.

The turbine comprises a support structure, first and second hydrofoils, a heaving-to-pitching assembly and a linear-to-rotary transmission system.

The first and second hydrofoils extend from the support structure, each hydrofoil being slidably and rotatably connected to the structure, to allow each of the hydrofoils to move linearly in a heaving motion and to oscillate about a spanwise axis in a pitching motion.

The heaving and pitching motions are quasi-sinusoidal, wherein for a given one of the hydrofoils, the heaving and pitching motions are out of phase by a pitch-heave motion phase, and wherein the respective heaving motions of the first and second hydrofoils are out of phase by an inter-hydrofoil phase.

The heaving-to-pitching assembly is for coupling the heaving motions of the first and second hydrofoils to the pitching motions of the second and first hydrofoils respectively, the pitch-heave motion phase being substantially equal to the inter-hydrofoil phase, the heaving motion of one of the hydrofoils thereby drives the pitching motion of the other hydrofoil.

The linear-to-rotary transmission system is operatively connected to the first and second hydrofoils and to the rotatable shaft. The heaving motions of the first and second hydrofoils therefore drive a rotational motion of the shaft.

According to another aspect of the invention, there is provided a method for converting kinetic energy from a fluid flow into mechanical energy. The method comprises the steps of:

a) providing a turbine including first and second hydrofoils, each of the hydrofoils being able to move linearly in a heaving motion, and being able to oscillate about a spanwise axis in a pitching motion. The heaving and pitching motions are quasi-sinusoidal, wherein :

  - for a given one of the hydrofoils, the heaving and pitching motions are out of phase by a pitch-heave motion phase, and
  - the respective heaving motions of the first and second hydrofoils are out of phase by an inter-hydrofoil phase;

b) coupling the heaving motions of the first and second hydrofoils to the pitching motions of the second and first hydrofoils respectively, with the pitch-heave motion phase being substantially equal to the inter-hydrofoil phase, the heaving motion of one of the hydrofoils thereby driving the pitching motion of the other hydrofoil; and

c) transforming the heaving motions of the hydrofoils into a rotational movement of a rotatable shaft, with linear-to-rotary transmission means.

According to yet another aspect of the invention, there is provided a propulsive system for transmitting mechanical energy from a rotatable driving shaft. The system comprises a support structure, first and second hydrofoils, a heaving-to-pitching assembly and a rotary-to-linear transmission system.

The first and second hydrofoils extend from the support structure, each hydrofoil being slidably and rotatably connected to the structure, to allow each of the hydrofoils to move linearly in a heaving motion, and to oscillate about a spanwise axis in a pitching motion. The heaving and pitching motions are quasi-sinusoidal, whereby for a given one of the hydrofoils, the heaving and pitching motions are out of phase by a pitch-heave motion phase, and the respective heaving motions of the first and second hydrofoils are out of phase by an inter-hydrofoil phase.

The heaving-to-pitching assembly is for coupling the heaving motions of the first and second hydrofoils to the pitching motions of the second and first hydrofoils respectively. The pitch-heave motion phase being substantially equal to the inter-hydrofoil phase, the heaving motion of one of the hydrofoils thereby drives the pitching motion of the other hydrofoil.

The rotary-to-linear transmission system is operatively connected to the rotatable shaft and to the first and second hydrofoils, the rotational motion of the driving shaft thereby driving the heaving and pitching motions of the hydrofoil.

Yet another aspect of the invention concerns a hydrofoil. The hydrofoil comprises a pair of foils extending in parallel, the foils being connected via rigid links.

Other features and advantages of the present invention will be better understood upon a reading of the preferred embodiments thereof with reference to the appended drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic view of two oscillating hydrofoils and a turbine with a horizontal axis rotor blade (PRIOR ART).

Figures 2A, 2B and 2C are perspective side views of a turbine shown in three different positions, respectively (PRIOR ART).

Figure 3 is a side perspective view of a turbine according to a preferred embodiment of the invention.

Figure 4 is a side perspective view of a turbine according to another preferred embodiment of the invention.

Figure 5 is a side perspective view of a turbine according to yet another preferred embodiment of the invention. Figure 5A is a front view of the hydrofoil of Figure 5, according to an embodiment of the invention. Figure 5B is a side view of the hydrofoil of Figure 5.

Figure 6A is a schematic view of a heaving-to-pitching assembly in combination with hydrofoils. Figure 6B is a graph representing the pitching and heaving motions of the hydrofoils of Figure 6A.

Figure 7 is a schematic view of part of the heaving-to-pitching assembly of Figure 6A. Figure 7A is a schematic view of a hydrofoil and its corresponding rotary actuator. Figure 7B is an alternative embodiment for the rotary actuator of Figure 7.

Figure 8 is a schematic view of part of a heaving-to-pitching assembly, according to another preferred embodiment. Figure 8A is an alternative embodiment for the rotary actuator of Figure 8.

Figure 9 is a schematic view of part of a linear-to-rotary transmission system, according to a preferred embodiment. Figures 9A and 9B are schematic views of another part of a linear-to-rotary transmission system, according to two preferred embodiments.

Figure 10 is a schematic view of components of a linear-to-rotary transmission system, according to another preferred embodiment.

Figure 11 is a side perspective view of a turbine, according to a preferred embodiment of the invention. Figure 11A is a schematic view of components of the turbine of Figure 11.

Figure 12 is a side perspective view of a turbine, according to another preferred embodiment of the invention. Figure 12A is a schematic view of components of the turbine of Figure 12.

Figure 13 is a side perspective view of a turbine, according to a yet another preferred embodiment of the invention. Figures 13A and 13B are schematic views of alternative embodiments of rotary actuators.

Figure 14 is a schematic view of a propulsive system, according to another preferred embodiment of the invention.

DESCRIPTION OF PREFERRED EMBODIMENTS OF THE INVENTION

In the following description, similar features in the drawings have been given similar reference numerals. In order to preserve clarity, certain elements may not be identified in some figures if they are already identified in a previous figure.

Referring to Figure 3, a first embodiment of a turbine 30 is shown, for converting kinetic energy from a fluid flow, represented by arrow 32, into mechanical energy. The mechanical energy can be used to drive a rotatable shaft from an electrical generator for example. The fluid can be of any type, such as air or water, but the fluid flow is preferably the current of an ocean or of a river.

The turbine 30 includes first and second hydrofoils 34a, 36a extending from a support structure, in this case a post 38, which is preferably in an upright vertical orientation. The hydrofoils 34a, 36b extend from one side of the post, and are substantially parallel to one another. Preferably, when the support structure 38 is a single post, another pair of first and second hydrofoils 34b, 36b extend on the opposite side of the post, such as to maximize the lifting surfaces of the turbine 30. Although shallower configurations are achieved when the post is in an upright or vertical orientation, the post may also be positioned in a horizontal orientation, the hydrofoils thus extending in a vertical orientation. The hydrofoils 34, 36 have an elongated and substantially planar body. Each of the hydrofoils 34, 36 also has an extending curved profile. They also have a symmetrical transversal cross-section.

Now referring to Figure 4, a second embodiment of a turbine 30 is shown. In this case, the support structure comprises two spaced-apart posts 38a, 38b, the first and the second hydrofoils 34, 36 extending between them. Each hydrofoil 34, 36 is slidably and rotatably connected to the structure, allowing each of the hydrofoils to move linearly in a heaving motion, and to oscillate about a spanwise axis in a pitching motion. In this configuration of the turbine 30, the heaving motion is vertical and each hydrofoil 34, 36 oscillates about a horizontal axis. Preferably, the hydrofoils 34, 36 each have a rectangular or untwisted configuration. Still preferably, the cross-section of each hydrofoil is symmetrical and its surface is curved.

Now turning to Figures 5, 5A and 5B, yet a third embodiment of a turbine 30 is shown. In this case, the hydrofoils 34, 36 each comprises a pair of foils 40a, 40b extending in parallel between the posts. The foils 40a, 40b are rigidly connected via rigid links, in this case reinforcement plates 42, which are distributed along the span of the hydrofoil. The ends of the hydrofoils are also provided with end plates 44a, 44b, which may facilitate the connection of the hydrofoils with other components of the turbine while reducing the undesirable effects of wingtip vortices. As best shown in Figure 5A, the multi-surface hydrofoil 34 is composed of a closely-spaced pair of foils, thus becoming a *bifoii* Such a configuration increases the rigidity of the hydrofoil 34, allowing the use of higher aspect ratios, which is the ratio of length (span) to width (chord) of the hydrofoil. A hydrofoil with a higher aspect ratio has increased lifting and thrusting capabilities while preserving its width and thus the compactness of the system. Best shown in Figure 5B, the two foils 40a, 40b are located on each side of the pitching axis 46 of the hydrofoil.

This configuration of the hydrofoil also favours a modular fabrication, where the overall length of the hydrofoil can be adapted, that is, increased or decreased, according to specific applications, using the same basic components. This modular configuration can also facilitate transport of the hydrofoil.

As will be appreciated, a hydrofoil 34, 36 can be composed of a single lifting surface, or alternatively incorporates multiple lifting surfaces rigidly connected to each other.

The mechanism involved in the oscillating motion of the hydrofoils can be divided in two main parts, according to their respective tasks. The first task implies the coupling of a linearly-oscillating or heaving-oscillating motion into an alternating rotary motion or pitching-motion. This first task is achieved with a heaving-to-pitching assembly, in which pitch-heave couplings are used to obtain a 1 degree-of-freedom system. The second part relates to the coupling of a linearly-oscillating motion into a rotary motion. This second part is achieved with a linear-to-rotary transmission system, using a power transmission link between the cyclical heaving motions of the hydrofoils and a rotating shaft.

The heaving-to-pitching assembly

Figures 6A to 8A show alternatives which can be considered in order to perform this first task, while Figures 9, 9A and 9B show alternatives to perform this second task. Figures 10 to 13 show the turbine with the components of the heaving-to-pitching assembly and of the linear-to-rotary transmission system when combined.

Referring now to Figures 6A, a schematic representation of a heaving-to-pitching assembly 48 in combination with the first and second hydrofoils 34, 36 is shown. The hydrofoils 34, 36 can slide and rotate, allowing them to move linearly in a heaving motion yi, y_2, and to oscillate about a spanwise axis in a pitching motion θ_1, θ_2. The heaving-to-pitching assembly allows the coupling of the heaving motions y_l, y_2 of the first and second hydrofoils 34, 36 to the pitching motions 0_2, 0_1 of the second and first hydrofoils 36, 34, respectively.

Figure 6B illustrates the heaving and pitching motions of the hydrofoils 34, 36 which are sinusoidal, or quasi-sinusoidal. In this graph, the heaving motion of the first hydrofoil 34 is represented by curve yi and its pitching motion by curve 0i. Similarly, for the second hydrofoil 36, its heaving motion is represented by curve y_2 and its pitching motion by curve 0_2.

As can be appreciated, for a given hydrofoil, its heaving and pitching motions are out of phase by a pitch-heave motion phase, which is equal to Pi/2, or 90 degrees which corresponds to T/4. It can also be observed that the heaving motion y_1 of the first hydrofoil 34 is out of phase relative to the heaving motion y_2 of the second hydrofoil 36, by an inter-hydrofoil phase. While the pitch-heave phase for a hydrofoil is typically Pi/2, the heaving-to-pitching assembly 48 sets the inter-foil phase between y_1 and y_2 to be also equal to Pi/2, making it possible to use the heaving motion of each foil to drive the pitching motion of its neighbour foil.

Back to Figure 6A, the heaving-to-pitching assembly 48 includes a pair of first and second linear actuators 50, 52, a pair of first and second rotary actuators 54, 56, and a heaving-to-pitching coupling system 58.

The first linear actuator 50 is connected to the first hydrofoil 34, and the second linear actuator 52 is connected to the second hydrofoil 36. When a hydrofoil 34, 36 moves linearly, in a heaving motion induced by water current for example, the corresponding linear actuator 50, 52 is driven by this heaving motion. In this case, the first and second linear actuators 50, 52 are hydraulic cylinders.

Similarly, the first rotary actuator 54 is connected to the first hydrofoil 34 and the second rotary actuator is connected to the second hydrofoil 36. The heaving-to-pitching coupling system 58, which preferably consists of hydraulic conduits, serves to couple the first linear actuator 50 to the second rotary actuator 56, and to couple the second linear actuator 52 to the first rotary actuator 54.

When the first hydrofoil 34 moves linearly under the flow of current, fluid is pushed outside the cylinder 50 through the conduits 58, the fluid in turn actuating the rotary actuator 56, thereby driving the pitching motion of the hydrofoil 36. The same relationship exists between the hydrofoil 36, the cylinder 52, and the rotary actuator 54. The hydraulic cylinders 50, 52 and rotary actuators 54, 56 are sized and configured such that the inter-foil phase is equal to the heaving-to-pitching phase, which is 90 degrees.

Preferably, as shown in Figures 3, 4 and 5, the hydraulic cylinders 50, 52, the rotary actuators 54, 56, and the coupling system 58 are housed within the base structure, in this case the post(s) 38.

In order to lower the operating pressure of the hydraulic cylinders, it is possible to double the components of the heaving-to-pitching assembly. In this case, embodiments such as those shown in Figures 4 and 5, ie with two posts 38, allow a first post 38a to house a first pair of linear actuators 50, 52, a first pair of rotary actuators 54, 56 and a first heaving-to-pitching assembly. The turbine also comprises a second post 38b that houses a second pair of linear actuators 50, 52, a second pair of rotary actuators 54, 56 and a second heaving-to-coupling system 58.

Referring now to Figures 7, the connection between the first hydrofoil 34, the first linear actuator 50 and the second rotary actuator 56 are shown. The pitching axis 46 of the hydrofoil 34 is rigidly connected to the double-sided cylinder 50 and to the rotary actuator 56. Both outlets 60a, 60b of the double-sided hydraulic cylinder 50 are connected to the inlets 62a, 62b of the rotary actuator 56. In this case, the rotary actuator 56 is a single vane actuator. In Figure 7, the second hydrofoil 36 is not shown for more clarity, but of course, the second hydrofoil 36 is indeed connected to the second rotary actuator 56, as shown in Figure 7A.

Preferably, the heaving-to-pitching assembly comprises a pitch-controlling mechanism 74 for controlling the pitching amplitude of the corresponding hydrofoil. In the present case, this mechanism 74 consists of stoppers 64a, 64b and of relief valves 66a, 66b. The fluid volume of the actuator 56 is designed to be slightly less than the fluid volume displaced by the hydraulic cylinder 50. This results in an automatic referencing system which operates when necessary. The extra fluid ensures that the vane 68 reaches the stoppers 64a, 64b, such that the preset maximum pitching amplitude is reached. Once the vane 68 touches one of the stoppers 64a, 64b, pressure rises and the extra fluid, which is preferably ecofriendly, such as surrounding water that has been filtered, is ejected through the relief valves 66a, 66b.

Figure 7B illustrates another embodiment of a pitch-controlling mechanism 74. In this case an active device is used. The volumetric pump 76, which is mechanically or otherwise controlled with a controller 78, periodically resets the pitch-heave motion phase.

Back to Figure 7, mechanical friction should be avoided wherever possible, in order to reduce maintenance. Preferably, hydrostatic bearings 70a, 70b are used instead of contact seals in every hydraulic cylinder and actuator. The hydrostatic bearings 70a, 70b are fed by an external pump 72 operating at a higher pressure than the hydraulic fluid. In addition to providing guidance and contactless operation of the hydraulic cylinder 50, the hydrostatic bearings ensure the replacement of any hydraulic fluid losses in the system. Alternatively, the vane 68 of the rotary actuator may also be equipped with a low-friction sealant, such as Teflon, UHMW, or the like.

Now turning to Figure 8, another type of rotary actuator is shown. In this case, the rotary actuator 56 includes a drum-and-cable mechanism. In such a mechanism, the pitching axis 47 of the second hydrofoil 36 is rigidly connected to the axis of the drum 82b. A cable 84 is rigidly connected to the drums 82a, 82b and is driven by a linear double rod hydraulic cylinder 86. Stoppers 64a, 64b and relief valves 66a, 66b can also be used with this type of rotary actuator 56, to control the pitching amplitude of the hydrofoil. Alternatively, as shown in Figure 8A, a controlled volumetric pump 76 can be used instead.

The linear-to-rotary transmission system

With reference to Figures 9, 9A and 9B, part of a linear-to-rotary transmission system 88 is shown. This part of the linear-to-rotary transmission system 88 operatively connects the first hydrofoil 34 and to the rotatable shaft 90, such that the heaving motion of the first hydrofoil can drive a rotational motion of the shaft

90. Of course, another part of the linear-to-rotary transmission system connects to the second hydrofoil 36, but this is not shown in the drawing for clarity purposes.

As shown in either one of the embodiments of Figures 9A and 9B, the linear-to-rotary transmission system 88 linked to the first hydrofoil 34 comprises a transmission actuator 92 operatively connected to said hydrofoil 34, which in this case is an hydraulic cylinder 92. This cylinder 92 is rigidly connected to the hydrofoil 34. The system 88 also includes linear-to-rotary transmission links 94, for transforming the linear motion of the transmission actuators 92 into the rotational motion of the shaft 90.

As can be appreciated, both embodiments of the linear-to-rotary links 94 shown in Figures 9A and 9B allow to couple the transmission actuator 92, and thus indirectly the hydrofoil 34, to the rotating shaft 90. The heaving power from the hydrofoil 34 is transformed in a rotational motion of the shaft, which can be part of an electrical generator, generating electricity.

With reference to Figure 9A, the transmission link 94 comprises two single-sided hydraulic cylinders 96a, 96b connected to crankshafts 98a, 98b. In the alternative embodiment shown in Figure 9B, the hydraulic cylinders 96a, 96b are connected to a hydraulic axial piston engine 100. Of course, other types of transmission links 94 may also be considered.

Back to Figure 9, the displaced volume of the double-sided hydraulic cylinder 92 preferably matches the total volume of the single-sided hydraulic cylinders 96a, 96b. However, to account for any mismatch in fluid volumes, relief valves 102a, 102b are added to each conduit.

Preferred embodiments of turbines and propulsive systems

Figure 10 shows another preferred embodiment of the linear-to-rotary transmission system 88 where the first and second transmission actuators 92, 93, and the first and second rotary actuators 54, 56 are connected to double-sided hydraulic cylinders 104a, 104b, 104c, and 104d. The cylinders 104a, 104c are connected to the same rod 106. Similarly cylinders 104b, 104d share rod 108.

This embodiment can be advantageous for applications where several turbines 30 are deployed together, such as in tidal farms, also called hydrokinetic turbine parks, where the linear-to-rotary transmission system of each turbine unit 30 connects to a same rotating shaft and electrical generator, with the relative motion phases between the turbines set in such a way as to further smoothes out the applied torque and rotation velocity.

Preferably, the hydraulic fluid used is low-pressure, around 150 psi, and consists of conditioned water or vegetable oil which limits energetic losses (minimal friction in hoses and minimal leaks in the ambient water) and ensures an environmentally friendly operation.

It should also be noted that the inter-foil phase of 90 degrees in a basic unit pair of hydrofoils implies a relative motion of each foil with its neighbouring foil. As a consequence, the hydraulic hoses interconnecting the hydraulic cylinders and the rotary actuators need to allow for this relative motion.

Advantageously, an inter-foil phase of 90 degrees allows avoiding that both hydrofoils 34, 36 reach their zero-production point, at top and bottom positions, at the same time, which effectively smoothes out the torque signal at the generator and makes the whole turbine self-starting at low water current velocity. Preferably, the heaving-to-pitching assembly and the linear-to-rotary transmission system 88 are compact enough so that most of the components fit inside the two side posts 38a, 38b forming the base structure. By doing so, most of the components are shielded from the flowing water, while the hydrofoils remain exposed.

With reference to Figure 11 and 11A, the heaving-to-pitching coupling system 58, which includes hydraulic conduits inter-connecting the linear actuators 50, 52 and rotary actuators 54, 56, may incorporate some length of coaxial sliding conduits 110, 112, 114, 116, so that the hydraulic circuit can account for the relative motion between both hydrofoils 34, 36 while maintaining a constant overall fluid volume. Figure 11A also provides a complete overview of the preferred mechanism with the rotary actuators 54, 46 rigidly connected via rigid links 118, 120 to their respective pitch-heave coupling hydraulic cylinders 50, 52, to their linear-to-rotary transmission cylinders 92, 93 and to their associated sliding conduits 110, 112, 114, 116.

Referring to Figure 12, in order to facilitate the alignment of the hydraulic cylinders which are part of the heaving-to-pitching assembly and of the linear-to-rotary transmission system, and in order to further improve the compactness of the entire mechanism, it is possible to rely on the use of coaxial hydraulic cylinders 122, 124. The coaxial cylinders 122, 124 can also be used in combination with sliding coaxial conduits, similar to the embodiment shown in Figure 11.

Referring to Figure 13, the turbine 30 can be further simplified by combining the hydraulic cylinders associated with a hydrofoil 34 or 36, for the heaving-to-pitching assembly and for the iinear-to-rotary transmission system, within a single hydraulic cylinder 126 or 128.

In this embodiment of the turbine 30, linear-to-rotary transmission links 94 are connected to the shaft 90 and the two transmission cylinders 126, 128 are each connected to the linear-to-rotary transmission links 94.

The first hydraulic cylinder 126 comprises a rod 130 and two pistons 134a, 134b located at both ends of the rod 130, each piston marking the boundaries of first and second chambers on both sides of the cylinder 126. The second hydraulic cylinder 128 has a similar configuration with rod 132, and pistons 136a, 136b. The rods 130, 132 are preferably articulated, to facilitate their alignment and displacement. Each rod 130, 132 is connected to a corresponding one of the hydrofoils 34, 36. For a given cylinder 126 or 128, the first chamber 138 is connected to its corresponding rotary actuator 56, 54 via the coupling means, and the second chamber 140 is connected to the transmission cylinders 96a, 96b. The rotatable shaft 90, moving in a constant rotational movement, can be coupled with any means 142 to an electric generator 144. In this preferred embodiment of the turbine 30, the hydraulic cylinders 126, 128 are part of both the heaving-to-pitching assembly and of the linear-to-rotary transmission system. Figures 13A and 13B show alternatives for the rotary actuators 54, 56. In Figure 13A, a rotary vane actuator 67 is represented, while in Figure 13B, a drum-and-cable mechanism 75 is shown.

Referring to Figure 14, an adaptation of the embodiment shown in Fig. 10 yields yet another embodiment of the invention, consisting of a propulsive system 146. The system 146 allows operating a first oscillating hydrofoil 34 with similar compact means of transmission for propulsion, rather than for power extraction. Although not shown, the same types of components and connections are made to a second hydrofoil, the two hydrofoils being coupled such as shown in Figure 10. This propulsive system 146 allows the transmission of mechanical energy from the rotatable driving shaft 90. The propulsive system comprises the same components of the turbine 30, that is: a support structure, first and second hydrofoils, a heaving-to-pitching assembly and a rotary-to-linear transmission system. In contrast with the turbine 30, in the propulsive system 146, it is the rotational motion of the driving shaft which in turn drives the heaving and pitching motions of the hydrofoil.

Method for converting kinetic energy from a fluid flow into mechanical energy

With reference to Figures 1 to 13, the method for converting kinetic energy from a fluid flow into mechanical energy requires a turbine which includes first and second hydrofoils, each being able to move linearly in a heaving motion, and to oscillate about a spanwise axis in a pitching motion, where the heaving and pitching motions are quasi-sinusoidal. For a given one of the hydrofoils, the heaving and pitching motions are out of phase by a pitch-heave motion phase, and the respective heaving motions of the first and second hydrofoils are out of phase by an inter-hydrofoil phase. The method requires the coupling of the heaving motions of the first and second hydrofoils to the pitching motions of the second and first hydrofoils respectively. This coupling is made with the pitch-heave motion phase being substantially equal to the inter-hydrofoil phase. This advantageously allows for the heaving motion of one of the hydrofoils to drive the pitching motion of the other hydrofoil. The method also requires the transformation of the heaving motions of the hydrofoils into a rotational movement of the rotatable shaft, using linear-to-rotary transmission means.

Preferably, the method includes the sub-steps of providing a pair of first and second linear actuators, a pair of first and second rotary actuators and a heaving-to-pitching coupling system. The first linear actuator is connected to the first hydrofoil, and the second linear actuator to the second hydrofoil, each of the first and second linear actuators being driven by the heaving motion of the corresponding hydrofoil. The first rotary actuator must also be connected to the first hydrofoil, and the second actuator to the second hydrofoil, each of the first and second rotary actuators driving the corresponding hydrofoil in the pitching motion. Finally, the first linear actuator is coupled to the second rotary actuator, and the second linear actuator to the first rotary actuator, using the heaving-to-pitching coupling system.

Still preferably, the method comprises a sub-step of providing two spaced-apart posts, the first and second hydrofoils extending between the posts. The first and second hydrofoils each comprises a pair of foils extending in parallel between the posts.

Performances are also improved when the pitch-heave motion phase, and the inter-hydrofoil phase are approximately 90 degrees. Preferably, the method further includes a step of controlling the pitching amplitudes of the first and second hydrofoils.

The turbine described above offers an obvious advantage in shallow water sites due to its rectangular harvesting plane, allowing the possibility to scale up the rated power by simply increasing the turbine hydrofoil span. Furthermore, the untwisted rectangular hydrofoils in the oscillating concept have a much simpler geometry, and are easier to produce than typical rotor blades.

For tidal operation, in which the turbine should be able to operate with both ebb and flood tides, i.e. in both opposite directions, the system can be reversed by rotating the hydrofoils by 180 degrees. This can be performed by mounting each foil's rotary actuator on an additional 0-180° hydraulic actuator which can be fed on demand by the pump feeding the hydrostatic bearings. Alternatively, the foil pitching-center junction with its structural spar may incorporate a clutch coupling. In such an embodiment, the 180° rotation of the foil may be initiated passively from the action of the water flow. To complete the turbine reversal, a change of phase is also necessary.

This is preferably accomplished by inverting the rotational motion of the electrical generator through the electrical drive.

Oscillating foils can generate efficient propulsive forces when operating with the proper pitching angles. The embodiment presented above may be used for propulsion purposes in applications aiming to generate thrust from oscillating hydrofoils. In such cases, the electrical generator would operate as a motor and work would be performed by the foils on the fluid, rather than energy being extracted from the fluid flow.

Numerous modifications could be made to the embodiments above without departing from the scope of the present invention.

CLAIMS:

1. A turbine for converting kinetic energy from a fluid flow into mechanical energy by driving a rotatable shaft, the turbine comprising:
   - a support structure;
   - first and second hydrofoils extending from said support structure, each hydrofoil being slidably and rotatably connected to said structure, for allowing each of the hydrofoils to move linearly in a heaving motion, and to oscillate about a spanwise axis in a pitching motion; said heaving and pitching motions being quasi-sinusoidal, wherein:
     - for a given one of said hydrofoils, the heaving and pitching motions are out of phase by a pitch-heave motion phase, and
     - the respective heaving motions of the first and second hydrofoils are out of phase by an inter-hydrofoil phase; and
   - a heaving-to-pitching assembly, for coupling the heaving motions of the first and second hydrofoils to the pitching motions of the second and first hydrofoils respectively, the pitch-heave motion phase being substantially equal to the inter-hydrofoil phase, the heaving motion of one of the hydrofoils thereby driving the pitching motion of the other hydrofoil; and
   - a linear-to-rotary transmission system operatively connected to the first and second hydrofoils and to the rotatable shaft, the heaving motions of the first and second hydrofoils thereby driving a rotational motion of the shaft.

2. The turbine according to claim 1, wherein the coupling-to-heaving assembly comprises:

- a pair of first and second linear actuators, said first linear actuator being connected to said first hydrofoil, and said second linear actuator being connected to said second hydrofoil, each of the first and second linear actuators being driven by the heaving motion of the corresponding hydrofoil;

- a pair of first and second rotary actuators, said first rotary actuator being connected to said first hydrofoil, and said second rotary actuator being connected to said second hydrofoil, each of the first and second rotary actuators driving the corresponding hydrofoil in the pitching motion; and

- a heaving-to-pitching coupling system for coupling the first linear actuator to the second rotary actuator, and for coupling the second linear actuator to the first rotary actuator.

3. The turbine according to claim 1 or 2, wherein the support structure comprises one post, the first and second hydrofoils extending on opposite sides of the post.

4. The turbine according to claim 1 or 2, wherein the support structure comprises two spaced-apart posts, the first and second hydrofoils extending between said posts.

5. The turbine according to any one of claims 1 to 4, wherein each of the hydrofoils has an elongated and substantially planar body.

6. The turbine according to any one of claims 1 to 5, wherein each of the hydrofoils has an extending curved profile.

7. The turbine according to claim 6, wherein each of said hydrofoils has a symmetrical transversal cross-section.

8. The turbine according to any one of claims 1 to 7, wherein the first and second hydrofoils each comprises a pair of foils extending in parallel.

9. The turbine according to claim 8, wherein for each of the hydrofoils, said pair of foils are rigidly connected via rigid links.

10. The turbine according to any one of claims 2 to 9, wherein said first and second linear actuators are hydraulic cylinders.

11. The turbine according to claim 10, wherein said hydraulic cylinders, and said first and second rotary actuators are housed within said base structure.

12. The turbine according to claim 2, wherein :

- the base structure comprises two spaced-apart posts, the first and second hydrofoils extending between said posts;
- the pair of first and second linear actuators is a first pair of linear actuators, the pair of first and second rotary actuators is a first pair of

rotary actuators, and the heaving-to-pitching coupling system is a first heaving-to-pitching coupling system, wherein said first pair of linear actuators, said first pair of rotary actuators and said first heaving-to-pitching system are housed in the first post;

the turbine further comprising:

- a second pair of first and second linear actuators, wherein for said second pair, the first linear actuator is connected to said first hydrofoil, and the second linear actuator is connected to said second hydrofoil;
- a second pair of first and second rotary actuators, wherein for said second pair, the first rotary actuator is connected to the first hydrofoil, and the second rotary actuator is connected to the second hydrofoil; and
- a second heaving-to-pitching coupling system, wherein for said second pairs of linear and rotary actuators, the first linear actuator is coupled to the second rotary actuator, and the second linear actuator is coupled the first rotary actuator; and

wherein said second pair of linear actuators, said second pair of rotary actuators, and said second heaving-to-pitching coupling system are housed in the second post.

13. The turbine according to any one of claims 2 to 12, wherein each of the rotary actuators is a single vane actuator.

14. The turbine according to any one of claims 2 to 12, wherein each of the rotary actuators includes a drum and cable mechanism.

15. The turbine according to claim 1 to 14, wherein the heaving-to-pitching assembly comprises a pitch-controlling mechanism for controlling a pitching amplitude of the corresponding hydrofoil.

16. The turbine according to claim 15, wherein said pitch-controlling mechanism comprises relief valves in combination with stoppers or a controllable volumetric pump.

17. The turbine according to any one of claims 1 to 16, wherein said pitch-heave motion phase, and said inter-hydrofoil phase are approximately 90 degrees.

18. The turbine according to claim 10, wherein each hydraulic cylinder is a coaxial hydraulic cylinder, thereby facilitating alignment of the first and second linear actuators.

19. The turbine according to any one of claims 1 to 18, wherein the linear-to-rotary transmission system comprises:

- at least two transmission actuators, each operatively connected to a corresponding one of the hydrofoils; and
- linear-to-rotary transmission links, for transforming a linear motion of the transmission actuators into the rotational motion of the shaft.

20. The turbine according to claim 10, wherein the linear-to-rotary transmission system comprises:

- linear-to-rotary transmission links connected to the shaft;

- at least two transmission cylinders, each connected to the linear-to-rotary transmission links; and

wherein:

- each hydraulic cylinder comprises a rod and two pistons located at both ends of the rod, each piston delimiting first and second chambers on both sides of the cylinder,

- each rod is connected to a corresponding one of the hydrofoils, said first chamber is connected to one of the rotary actuators via the heaving-to-pitching coupling means, and said second chamber is connected to one of said at least two transmission cylinders;

each hydraulic cylinder thereby being part of the linear-to-rotary transmission system.

21. The turbine according to claim 20, wherein for each of the hydraulic cylinders, the rod is articulated.

22. The turbine according to any one of claims 1 to 21, wherein the fluid flow is a flow of water and the turbine is a hydrokinetic turbine.

23. The turbine according to any one of claims 1 to 21, where the fluid flow is a flow of air and the turbine is a wind turbine.

24. A method for converting kinetic energy from a fluid flow into mechanical energy, the method comprising the steps of:

a) providing a turbine including first and second hydrofoils, each of the hydrofoils being able to move linearly in a heaving motion, and being able to oscillate about a spanwise axis in a pitching motion, said heaving and pitching motions being quasi-sinusoidal, wherein:
   - for a given one of said hydrofoils, the heaving and pitching motions are out of phase by a pitch-heave motion phase, and
   - the respective heaving motions of the first and second hydrofoils are out of phase by an inter-hydrofoil phase;

b) coupling the heaving motions of the first and second hydrofoils to the pitching motions of the second and first hydrofoils respectively, with the pitch-heave motion phase being substantially equal to the inter-hydrofoil phase, the heaving motion of one of the hydrofoils thereby driving the pitching motion of the other hydrofoil; and

c) transforming the heaving motions of the hydrofoils into a rotational movement of a rotatable shaft, with linear-to-rotary transmission means.

25. The method according to claim 24, wherein step b), comprises the sub-steps of:

i) providing a pair of first and second linear actuators, a pair of first and second rotary actuators and a heaving-to-pitching coupling system;

ii) connecting said first linear actuator to said first hydrofoil, and said second linear actuator to said second hydrofoil, each of the first and second linear actuators being driven by the heaving motion of the corresponding hydrofoil;

iii) connecting said first rotary actuator to said first hydrofoil, and said second actuator to said second hydrofoil, each of the first and second rotary actuators driving the corresponding hydrofoil in the pitching motion; and

iv) coupling the first linear actuator to the second rotary actuator, and the second linear actuator to the first rotary actuator with the heaving-to-pitching coupling system.

26. The method according to claims 24 or 25, wherein step a) comprises a sub-step of providing two spaced-apart posts, the first and second hydrofoils extending between said posts.

27. The method according to any one of claims 24 to 26, wherein step a) the first and second hydrofoils each comprises a pair of foils extending in parallel.

28. The method according to any one of claims 24 to 27, wherein in step b), said pitch-heave motion phase, and said inter-hydrofoil phase are approximately 90 degrees.

29. The method according to any one of claims 24 to 28, further comprising a step of controlling respective pitching amplitudes of the first and second hydrofoils.

30. A propulsive system for transmitting mechanical energy from a rotatable driving shaft , the system comprising:

- a support structure;
- first and second hydrofoils extending from said support structure, each hydrofoil being slidably and rotatably connected to said structure, for allowing each of the hydrofoils to move linearly in a heaving motion, and to oscillate about a spanwise axis in a pitching motion; said heaving and pitching motions being quasi-sinusoidal, wherein:
  - for a given one of said hydrofoils, the heaving and pitching motions are out of phase by a pitch-heave motion phase, and
  - the respective heaving motions of the first and second hydrofoils are out of phase by an inter-hydrofoil phase; and
- a heaving-to-pitching assembly, for coupling the heaving motions of the first and second hydrofoils to the pitching motions of the second and first hydrofoils respectively, the pitch-heave motion phase being substantially equal to the inter-hydrofoil phase, the heaving motion of one of the hydrofoils thereby driving the pitching motion of the other hydrofoil; and
- a rotary-to-linear transmission system operatively connected to the rotatable shaft and to the first and second hydrofoils, the rotational motion

of the driving shaft thereby driving the heaving and pitching motions of the hydrofoil.

31. A hydrofoil comprising a pair of foils extending in parallel, said foils being connected via rigid links.

32. The hydrofoil according to claim 31, wherein each of said foils has an elongated and substantially planar body.

33. The hydrofoil according to claim 31 or 32, wherein each of said foils has an extending curved profile.

34. The hydrofoil according to any one of claims 31 to 33, wherein each of said foils has a symmetrical transversal cross-section.

35. The hydrofoil according to any one of claims 31 to 34, wherein the rigid links comprise reinforcing plates distributed spanwise along the hydrofoil, for providing added foil rigidity.

AMENDED CLAIMS
received by the International Bureau on 13 January 2012 (13.01.2012)

1. A turbine for converting kinetic energy from a fluid flow into mechanical energy by driving a rotatable shaft, the turbine comprising:
   - a support structure;
   - first and second hydrofoils extending from said support structure, each hydrofoil being slidably and rotatably connected to said structure, for allowing each of the hydrofoils to move linearly in a heaving motion, and to oscillate about a spanwise axis in a pitching motion; said heaving and pitching motions being quasi-sinusoidal, wherein:
     - for a given one of said hydrofoils, the heaving and pitching motions are out of phase by a pitch-heave motion phase, and
     - the respective heaving motions of the first and second hydrofoils are out of phase by an inter-hydrofoii phase; and
   - a heaving-to-pitching assembly, for coupling the heaving motions of the first and second hydrofoils to the pitching motions of the second and first hydrofoils respectively, the pitch-heave motion phase being substantially equal to the inter-hydrofoil phase, the heaving motion of one of the hydrofoils thereby driving the pitching motion of the other hydrofoil; and
   - a linear-to-rotary transmission system operatively connected to the first and second hydrofoils and to the rotatable shaft, the heaving motions of the first and second hydrofoils thereby driving a rotational motion of the shaft.

2. The turbine according to claim 1, wherein the heaving-to-pitching assembly comprises:

   - a pair of first and second linear actuators, said first linear actuator being connected to said first hydrofoil, and said second linear actuator being connected to said second hydrofoil, each of the first and second linear actuators being driven by the heaving motion of the corresponding hydrofoil;

   - a pair of first and second rotary actuators, said first rotary actuator being connected to said first hydrofoil, and said second rotary actuator being connected to said second hydrofoil, each of the first and second rotary actuators driving the corresponding hydrofoil in the pitching motion; and

   - a heaving-to-pitching coupling system for coupling the first linear actuator to the second rotary actuator, and for coupling the second linear actuator to the first rotary actuator.

3. The turbine according to claim 1 or 2, wherein the support structure comprises one post, the first and second hydrofoils extending on opposite sides of the post.

4. The turbine according to claim 1 or 2, wherein the support structure comprises two spaced-apart posts, the first and second hydrofoils extending between said posts.

5. The turbine according to any one of claims 1 to 4, wherein each of the hydrofoils has an elongated and substantially planar body.

6. The turbine according to any one of claims 1 to 5, wherein each of the hydrofoils has an extending curved profile.

7. The turbine according to claim 6, wherein each of said hydrofoils has a symmetrical transversal cross-section.

8. The turbine according to any one of claims 1 to 7, wherein the first and second hydrofoils each comprises a pair of foils extending in parallel.

9. The turbine according to claim 8, wherein for each of the hydrofoils, said pair of foils are rigidly connected via rigid links.

10. The turbine according to any one of claims 2 to 9, wherein said first and second linear actuators are hydraulic cylinders.

11. The turbine according to claim 10, wherein said hydraulic cylinders, and said first and second rotary actuators are housed within said support structure.

12. The turbine according to claim 2, wherein :

- the support structure comprises two spaced-apart posts, the first and second hydrofoils extending between said posts;

- the pair of first and second linear actuators is a first pair of linear actuators, the pair of first and second rotary actuators is a first pair of rotary actuators, and the heaving-to-pitching coupling system is a first heaving-to-pitching coupling system, wherein said first pair of linear actuators, said first pair of rotary actuators and said first heaving-to-pitching system are housed in the first post;

the turbine further comprising:

- a second pair of first and second linear actuators, wherein for said second pair, the first linear actuator is connected to said first hydrofoil, and the second linear actuator is connected to said second hydrofoil;
- a second pair of first and second rotary actuators, wherein for said second pair, the first rotary actuator is connected to the first hydrofoil, and the second rotary actuator is connected to the second hydrofoil; and
- a second heaving-to-pitching coupling system, wherein for said second pairs of linear and rotary actuators, the first linear actuator is coupled to the second rotary actuator, and the second linear actuator is coupled the first rotary actuator; and

wherein said second pair of linear actuators, said second pair of rotary actuators, and said second heaving-to-pitching coupling system are housed in the second post.

13. The turbine according to any one of claims 2 to 12, wherein each of the rotary actuators is a single vane actuator.

14. The turbine according to any one of claims 2 to 12, wherein each of the rotary actuators includes a drum and cable mechanism.

15. The turbine according to any one of claims 1 to 14, wherein the heaving-to-pitching assembly comprises a pitch-controlling mechanism for controlling a pitching amplitude of the corresponding hydrofoil.

16. The turbine according to claim 15, wherein said pitch-controlling mechanism comprises relief valves in combination with stoppers or a controllable volumetric pump.

17. The turbine according to any one of claims 1 to 16, wherein said pitch-heave motion phase, and said inter-hydrofoil phase are approximately 90 degrees.

18. The turbine according to claim 10, wherein each hydraulic cylinder is a coaxial hydraulic cylinder, thereby facilitating alignment of the first and second linear actuators.

19. The turbine according to any one of claims 1 to 18, wherein the linear-to-rotary transmission system comprises:

- at least two transmission actuators, each operatively connected to a corresponding one of the hydrofoils; and
- linear-to-rotary transmission links, for transforming a linear motion of the transmission actuators into the rotational motion of the shaft.

20. The turbine according to claim 10, wherein the linear-to-rotary transmission system comprises:

- linear-to-rotary transmission links connected to the shaft;
- at least two transmission cylinders, each connected to the linear-to-rotary transmission links; and

wherein:

- each hydraulic cylinder comprises a rod and two pistons located at both ends of the rod, each piston delimiting first and second chambers on both sides of the cylinder,
- each rod is connected to a corresponding one of the hydrofoils, said first chamber is connected to one of the rotary actuators via the heaving-to-pitching coupling means, and said second chamber is connected to one of said at least two transmission cylinders;

each hydraulic cylinder thereby being part of the linear-to-rotary transmission system.

21. The turbine according to claim 20, wherein for each of the hydraulic cylinders, the rod is articulated.

22. The turbine according to any one of claims 1 to 21, wherein the fluid flow is a flow of water and the turbine is a hydrokinetic turbine.

23. The turbine according to any one of claims 1 to 21, where the fluid flow is a flow of air and the turbine is a wind turbine.

24. A method for converting kinetic energy from a fluid flow into mechanical energy, the method comprising the steps of:

a) providing a turbine including first and second hydrofoils, each of the hydrofoils being able to move linearly in a heaving motion, and being able to oscillate about a spanwise axis in a pitching motion, said heaving and pitching motions being quasi-sinusoidal, wherein:
    - for a given one of said hydrofoils, the heaving and pitching motions are out of phase by a pitch-heave motion phase, and
    - the respective heaving motions of the first and second hydrofoils are out of phase by an inter-hydrofoil phase;
b) coupling the heaving motions of the first and second hydrofoils to the pitching motions of the second and first hydrofoils respectively, with the pitch-heave motion phase being substantially equal to the inter-hydrofoil phase, the heaving motion of one of the hydrofoils thereby driving the pitching motion of the other hydrofoil; and

c) transforming the heaving motions of the hydrofoils into a rotational movement of a rotatable shaft, with linear-to-rotary transmission means.

25. The method according to claim 24, wherein step b), comprises the sub-steps of:

i) providing a pair of first and second linear actuators, a pair of first and second rotary actuators and a heaving-to-pitching coupling system;

ii) connecting said first linear actuator to said first hydrofoil, and said second linear actuator to said second hydrofoil, each of the first and second linear actuators being driven by the heaving motion of the corresponding hydrofoil;

iii) connecting said first rotary actuator to said first hydrofoil, and said second actuator to said second hydrofoil, each of the first and second rotary actuators driving the corresponding hydrofoil in the pitching motion; and

iv) coupling the first linear actuator to the second rotary actuator, and the second linear actuator to the first rotary actuator with the heaving-to-pitching coupling system.

26. The method according to claims 24 or 25, wherein step a) comprises a sub-step of providing two spaced-apart posts, the first and second hydrofoils extending between said posts.

27. The method according to any one of claims 24 to 26, wherein step a) the first and second hydrofoils each comprises a pair of foils extending in parallel.

28. The method according to any one of claims 24 to 27, wherein in step b), said pitch-heave motion phase, and said inter-hydrofoil phase are approximately 90 degrees.

29, The method according to any one of claims 24 to 28, further comprising a step of controlling respective pitching amplitudes of the first and second hydrofoils.

30, A propulsive system for transmitting mechanical energy from a rotatable driving shaft , the system comprising:

- a support structure;
- first and second hydrofoils extending from said support structure, each hydrofoil being slidably and rotatably connected to said structure, for allowing each of the hydrofoils to move linearly in a heaving motion, and to oscillate about a spanwise axis in a pitching motion; said heaving and pitching motions being quasi-sinusoidal, wherein:
  - for a given one of said hydrofoils, the heaving and pitching motions are out of phase by a pitch-heave motion phase, and
  - the respective heaving motions of the first and second hydrofoils are out of phase by an inter-hydrofoil phase; and
- a heaving-to-pitching assembly, for coupling the heaving motions of the first and second hydrofoils to the pitching motions of the second and first hydrofoils respectively, the pitch-heave motion phase being substantially equal to the inter-hydrofoil phase, the heaving motion of one of the hydrofoils thereby driving the pitching motion of the other hydrofoil; and
- a rotary-to'linear transmission system operatively connected to the rotatable shaft and to the first and second hydrofoils, the rotational motion

of the driving shaft thereby driving the heaving and pitching motions of the hydrofoil.

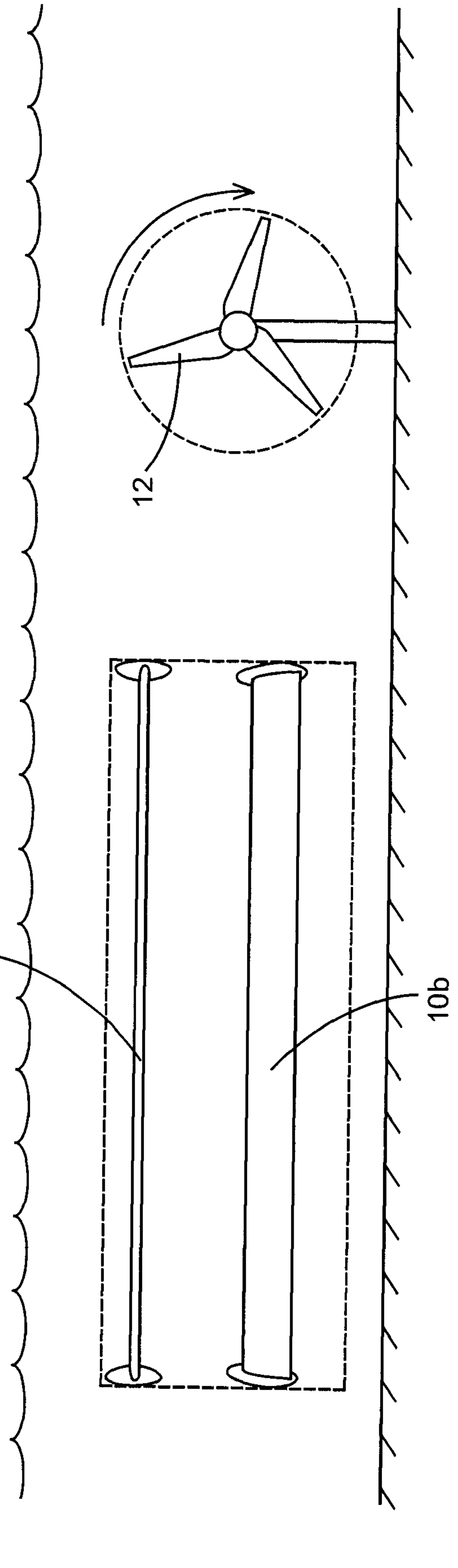


FIG. 1
(PRIOR ART)

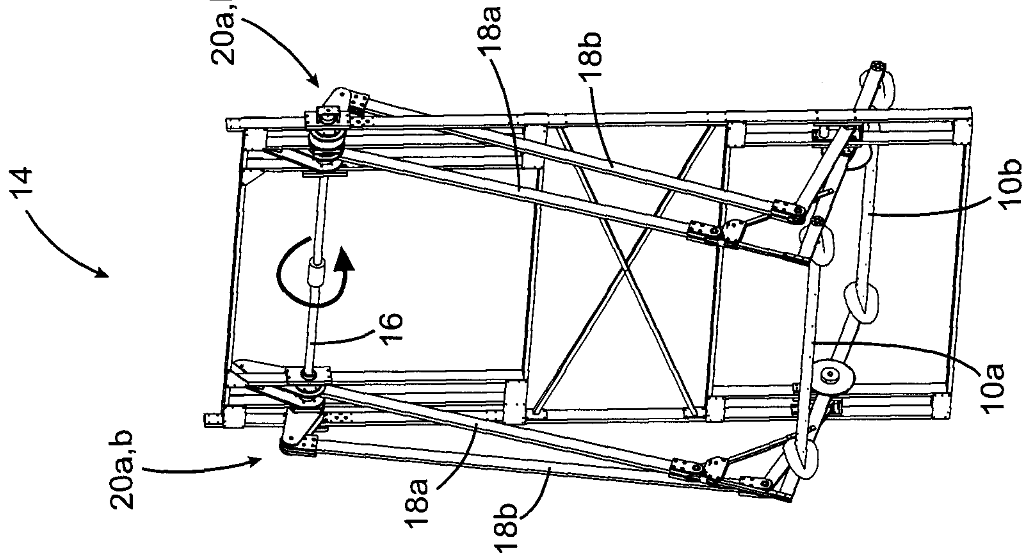


FIG. 2C
(PRIOR ART)

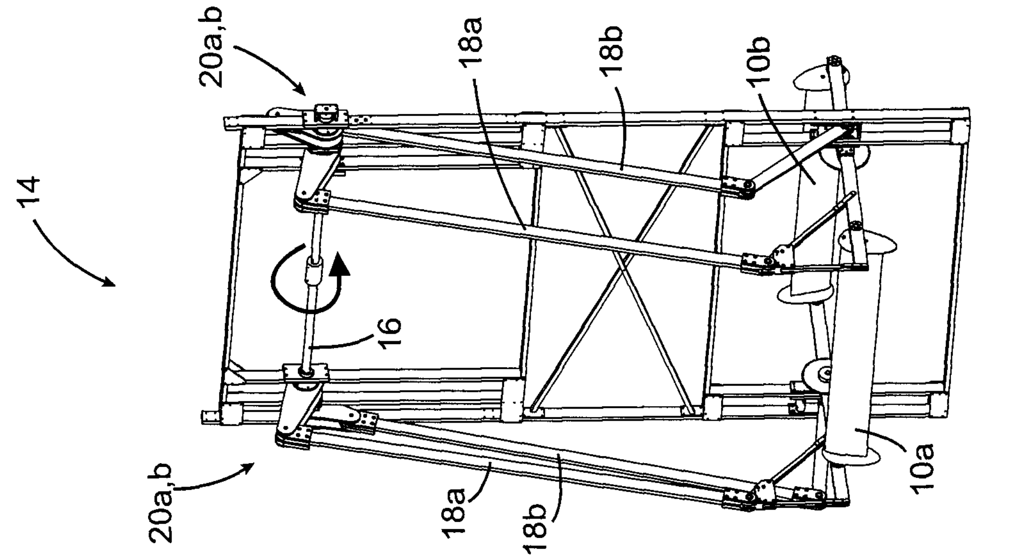


FIG. 2B
(PRIOR ART)

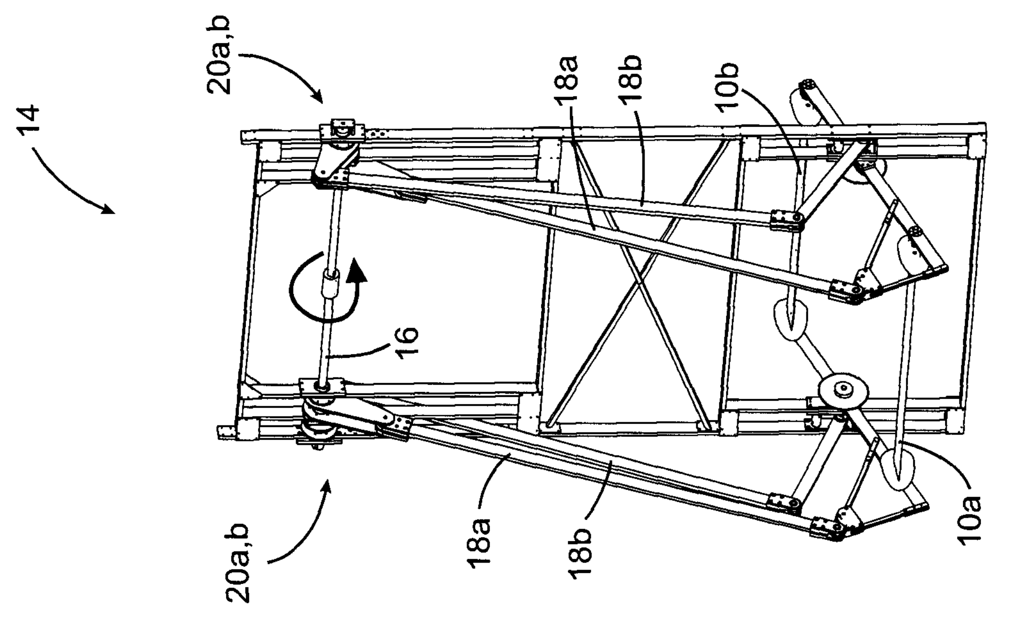


FIG. 2A
(PRIOR ART)

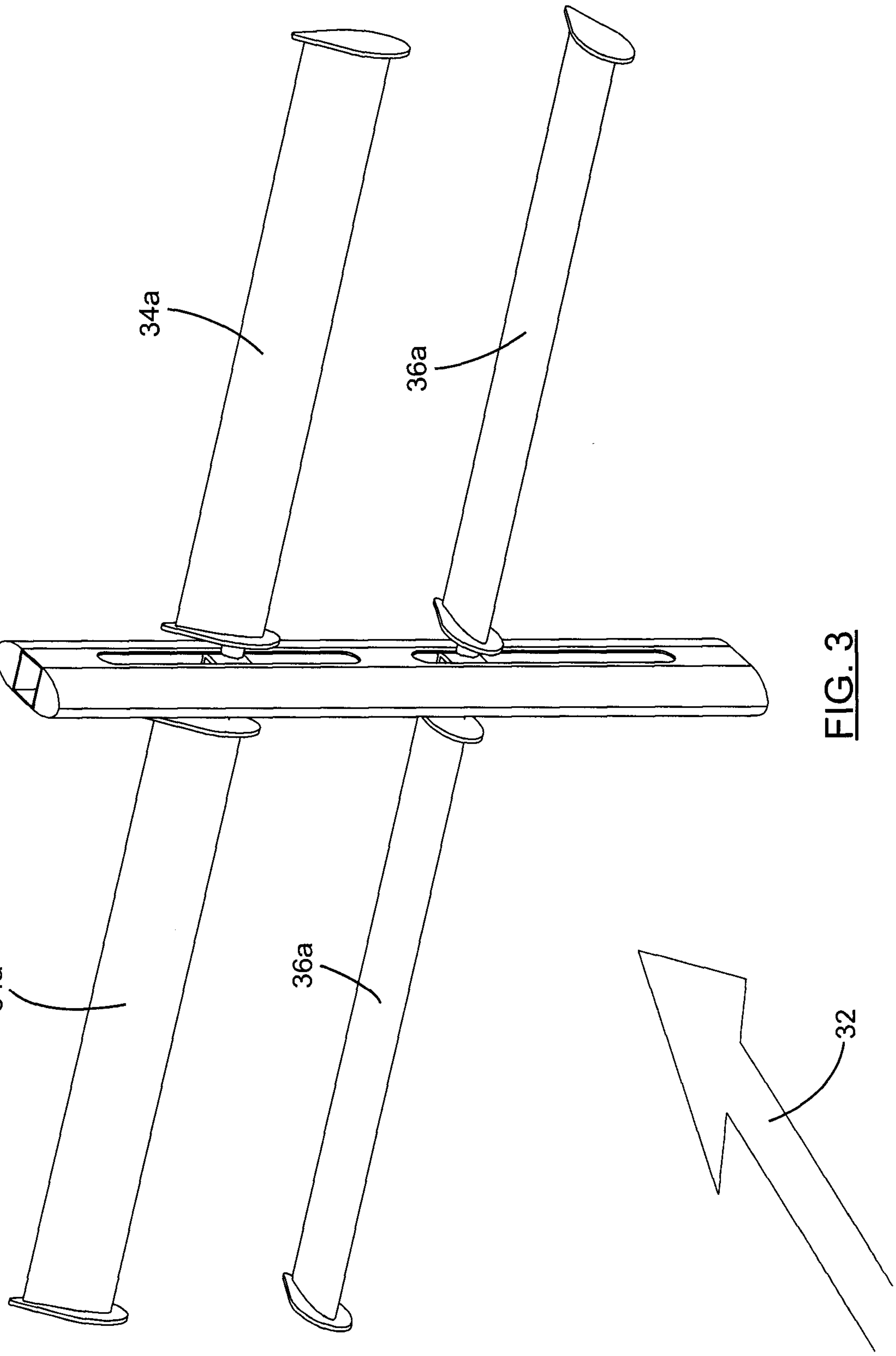


FIG. 3

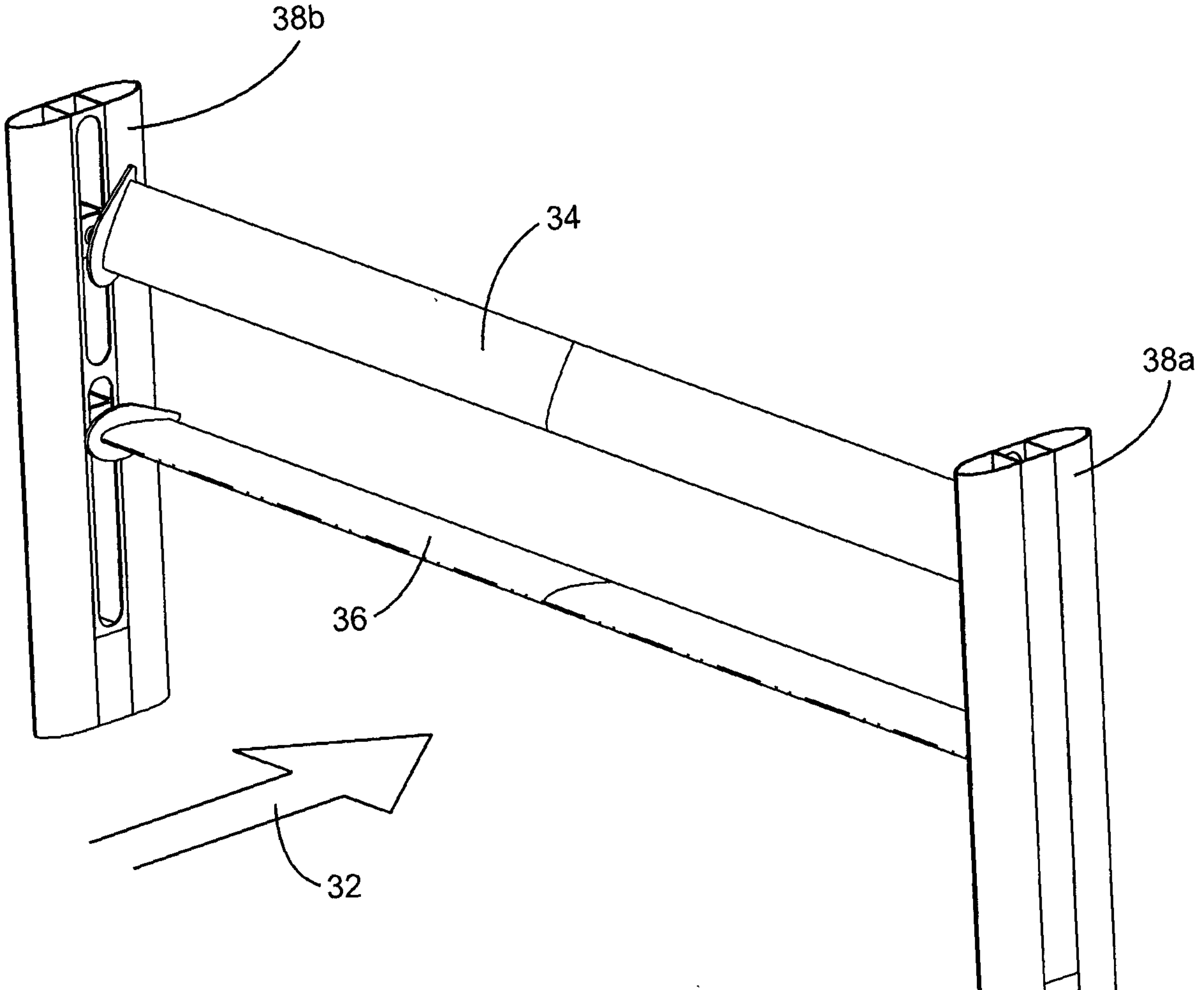


FIG. 4

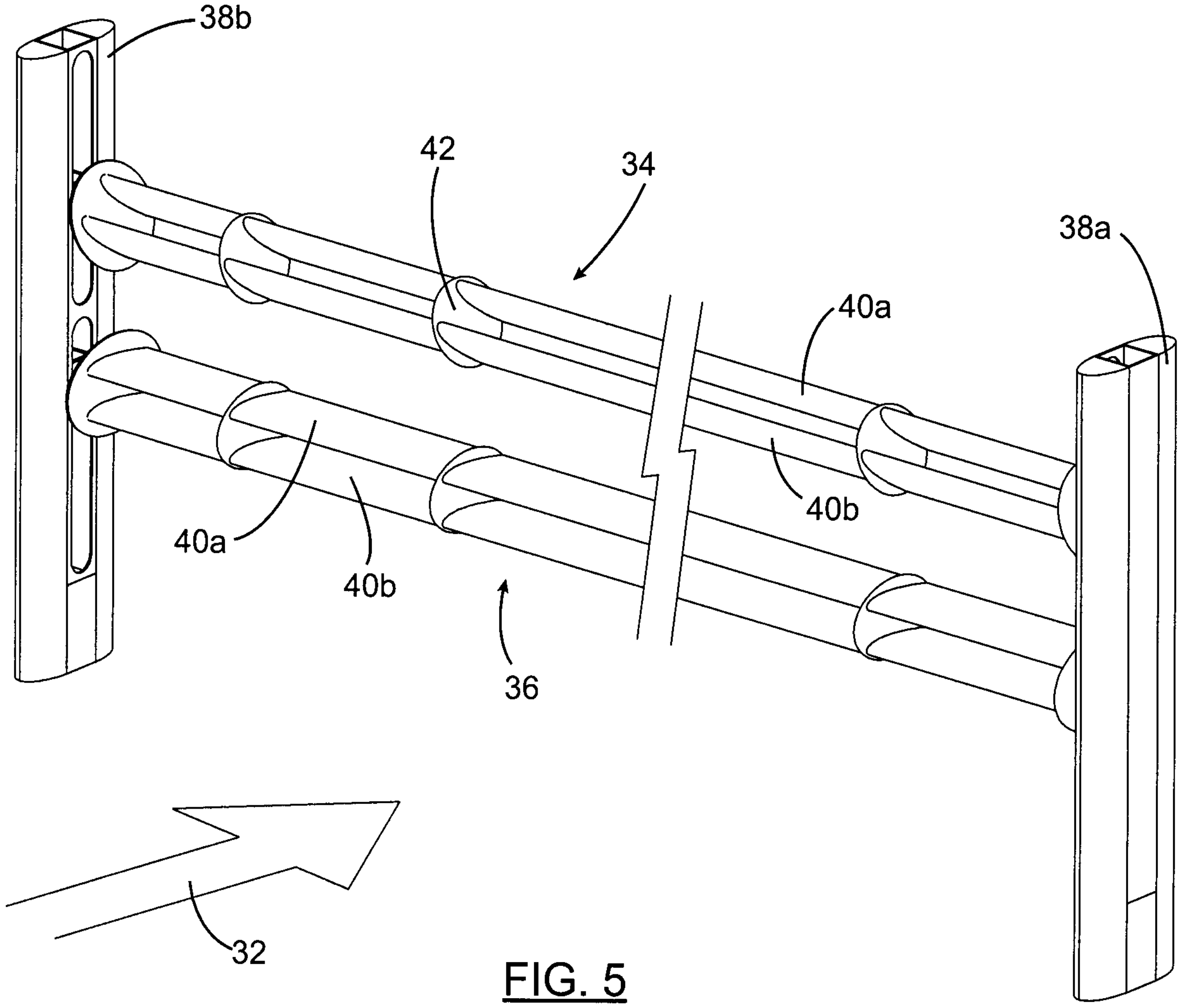


FIG. 5

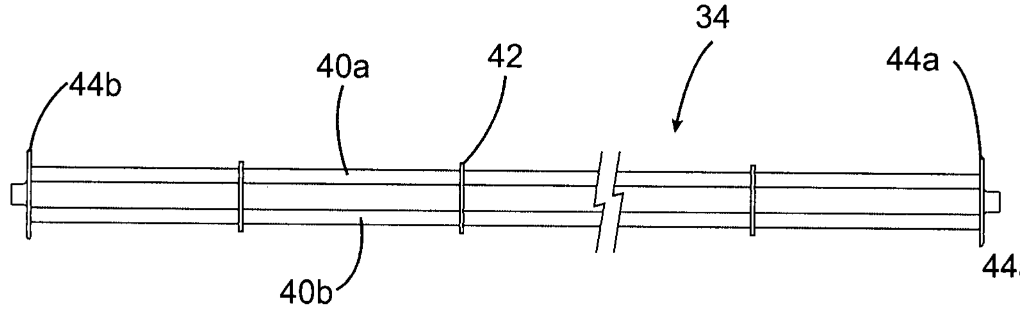


FIG. 5A

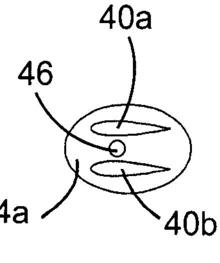
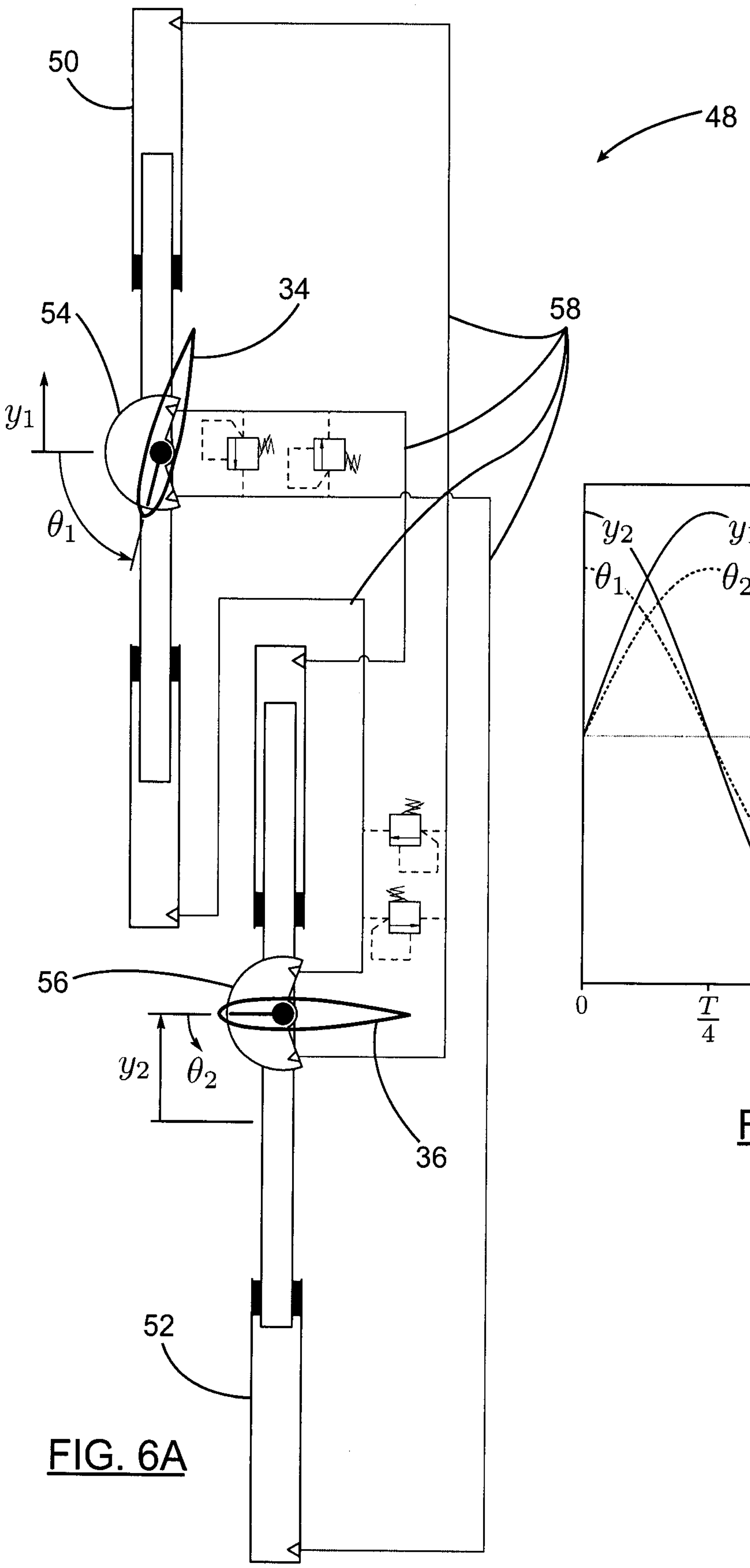
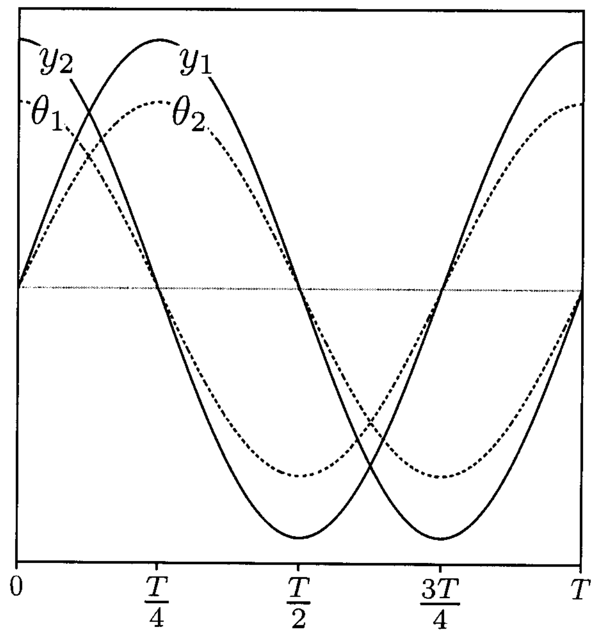


FIG. 5B



50
48
34
54
58
y_1
θ_1
56
y_2
θ_2
36
52

FIG. 6A



y_2
y_1
θ_1
θ_2
0
$\frac{T}{4}$
$\frac{T}{2}$
$\frac{3T}{4}$
T

FIG. 6B

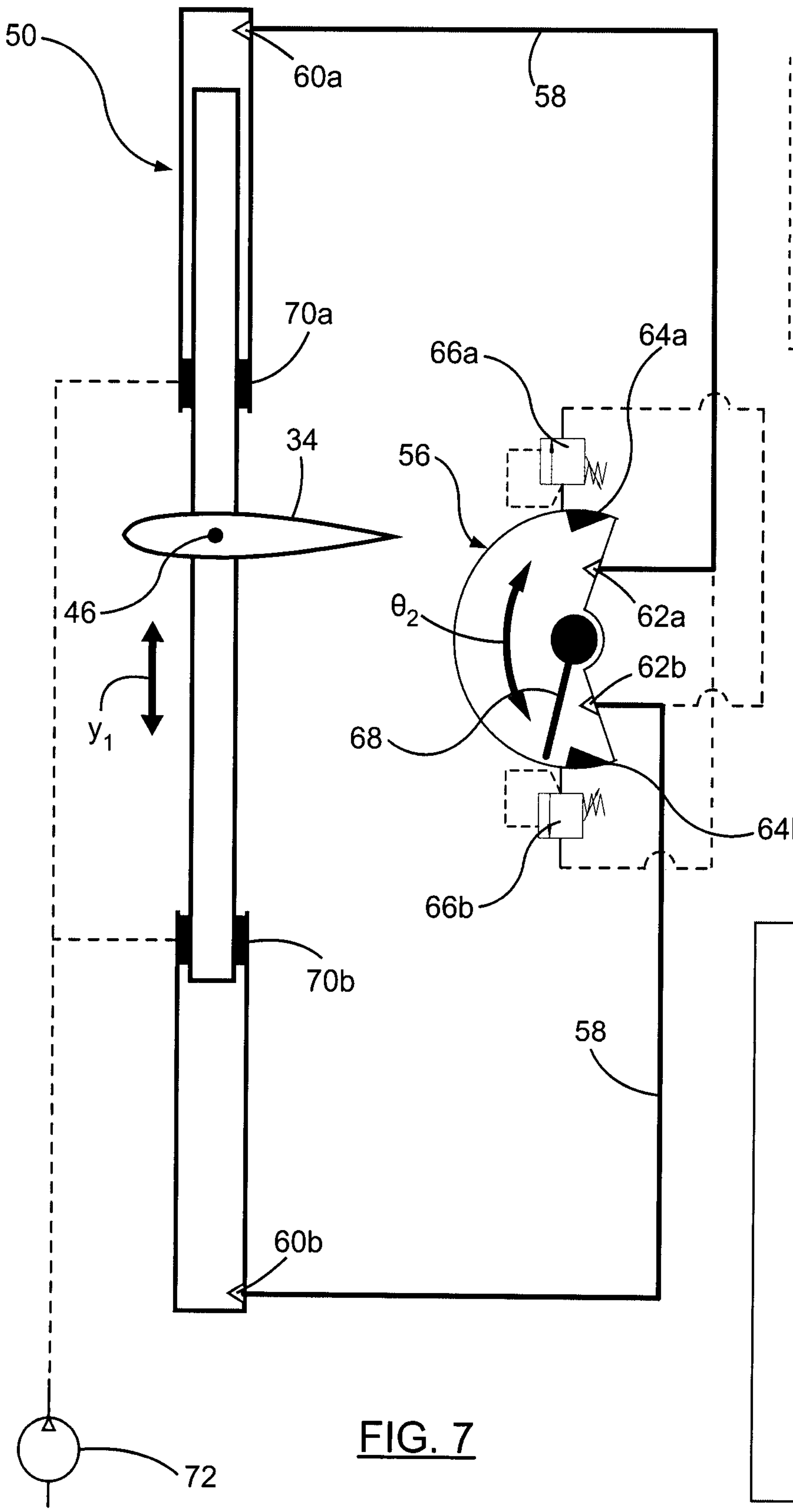


FIG. 7

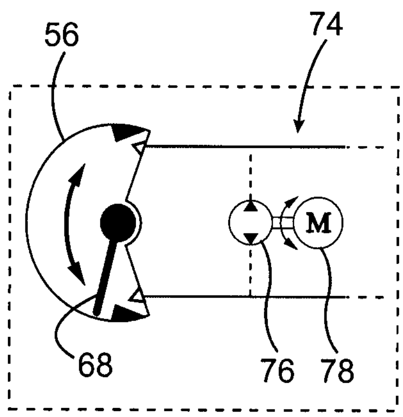


FIG. 7B

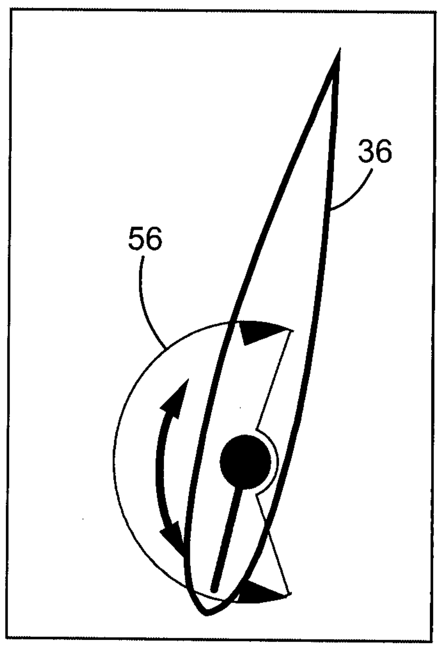


FIG. 7A

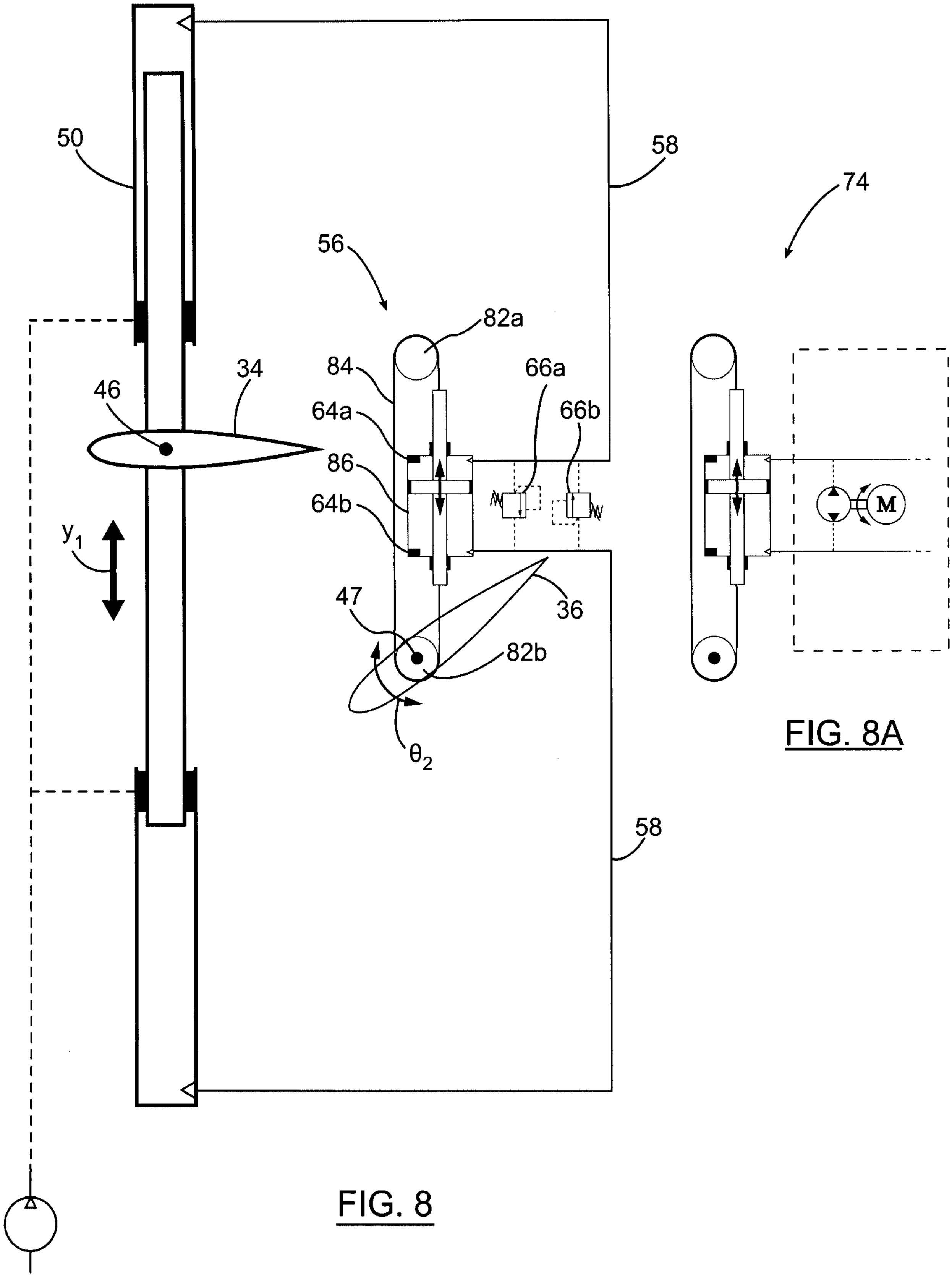


FIG. 8A

FIG. 8

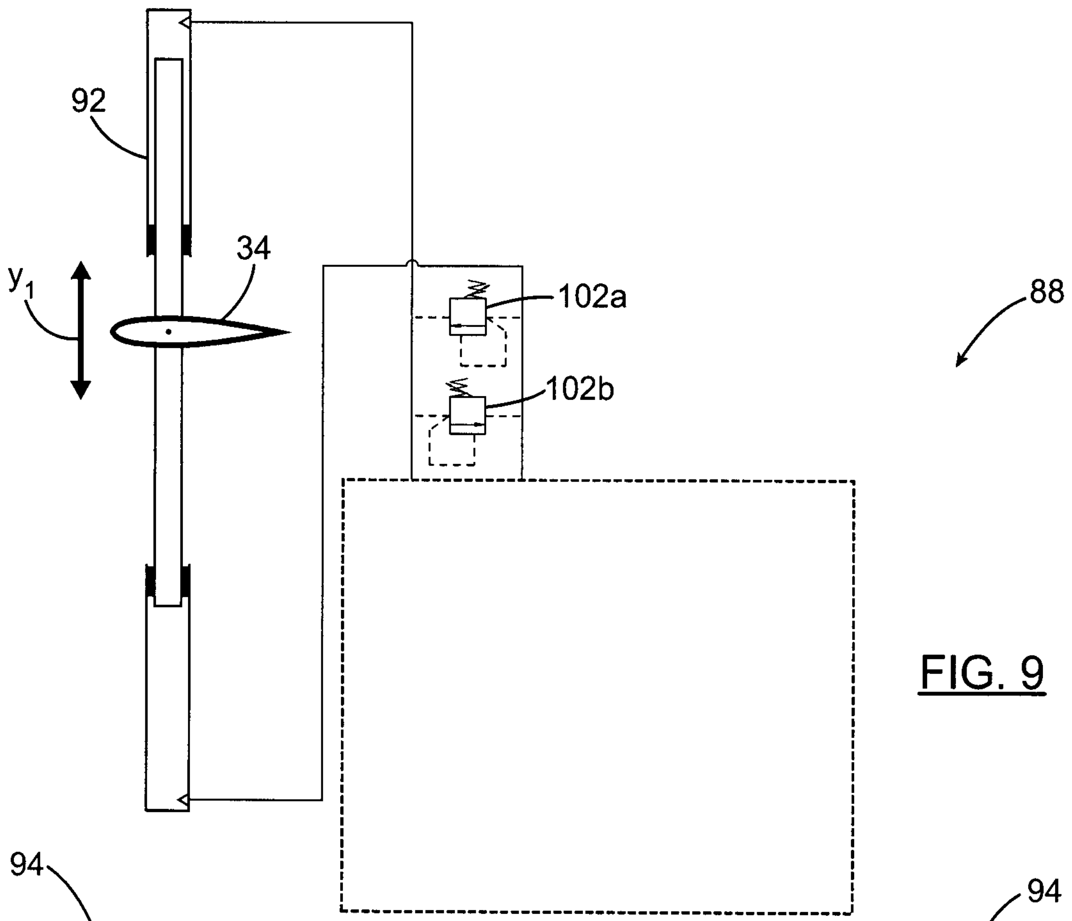


FIG. 9

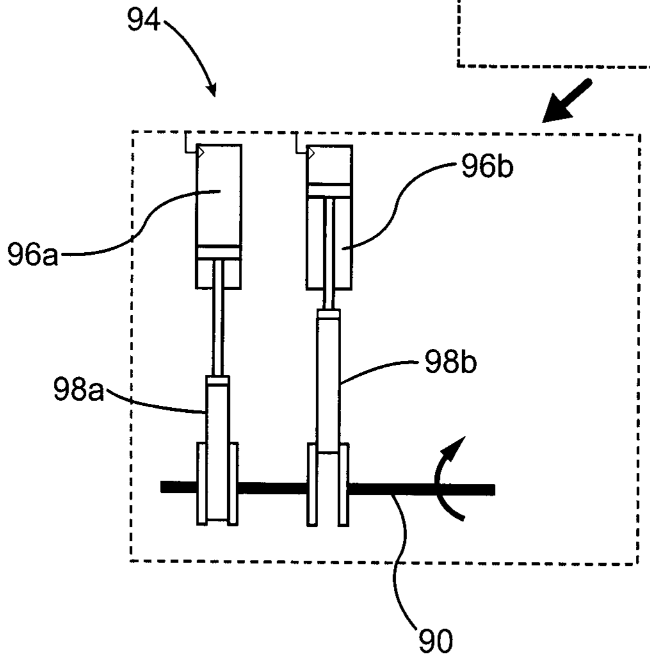


FIG. 9A

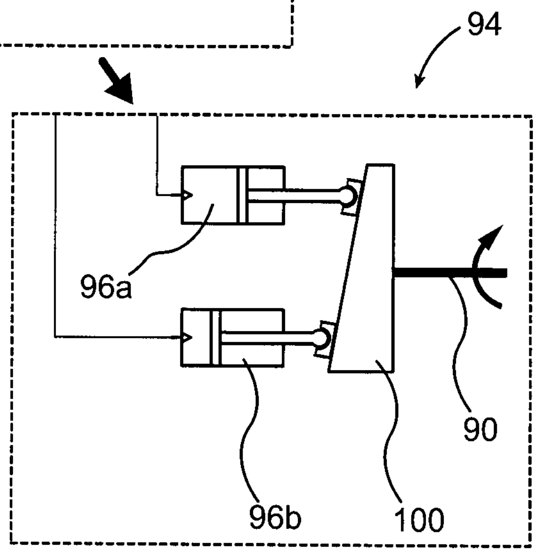


FIG. 9B

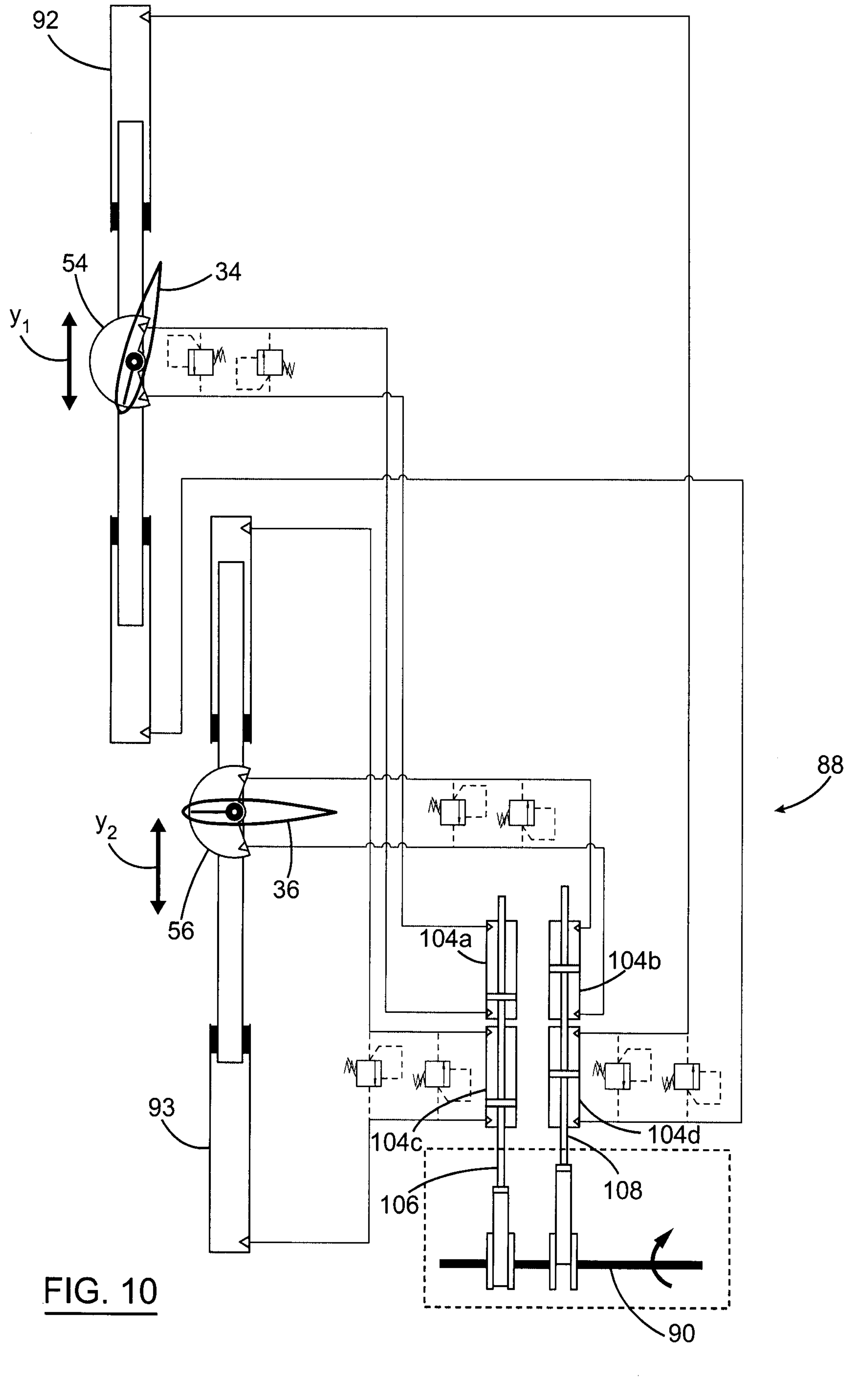


FIG. 10

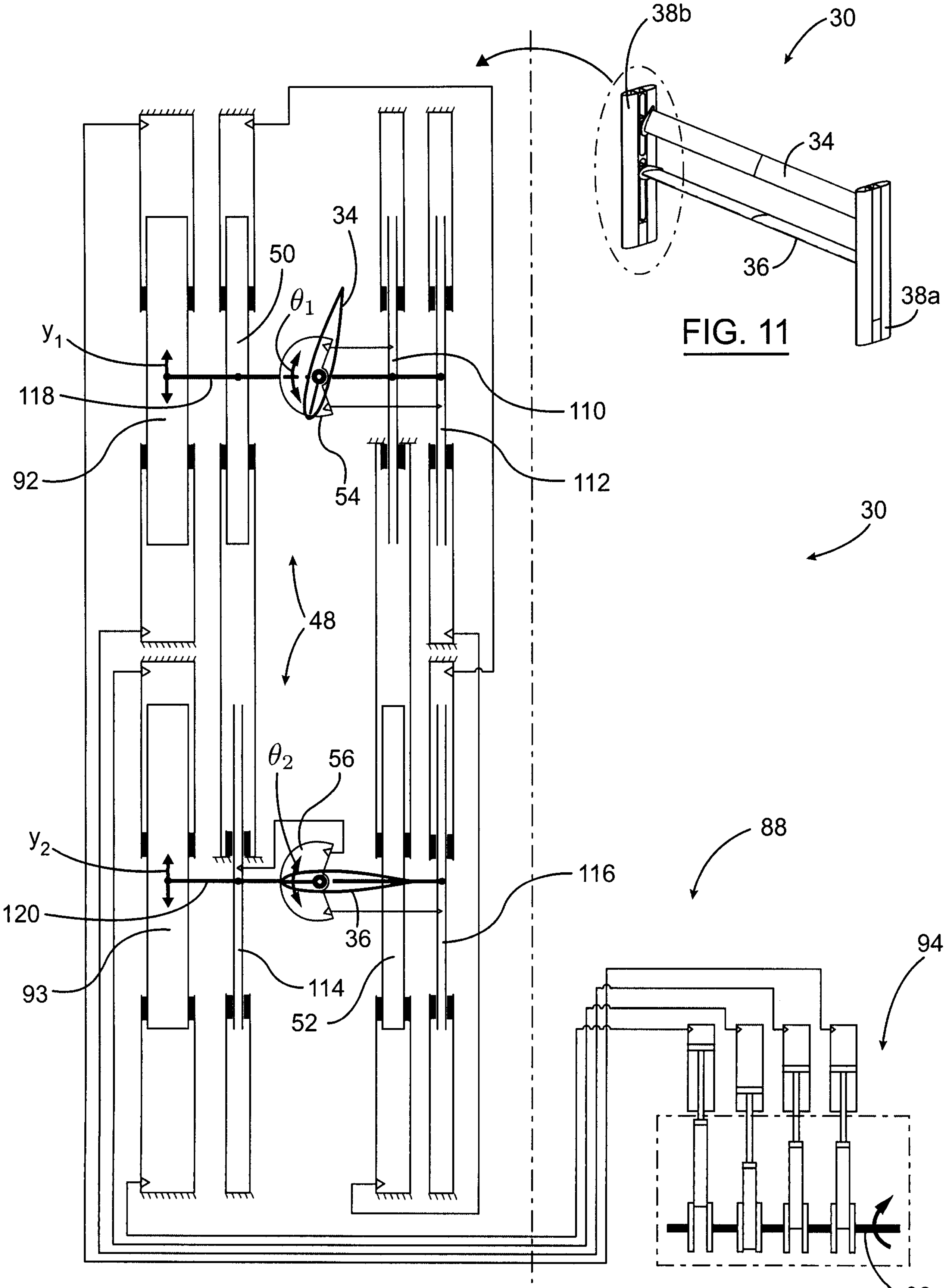


FIG. 11

FIG. 11A

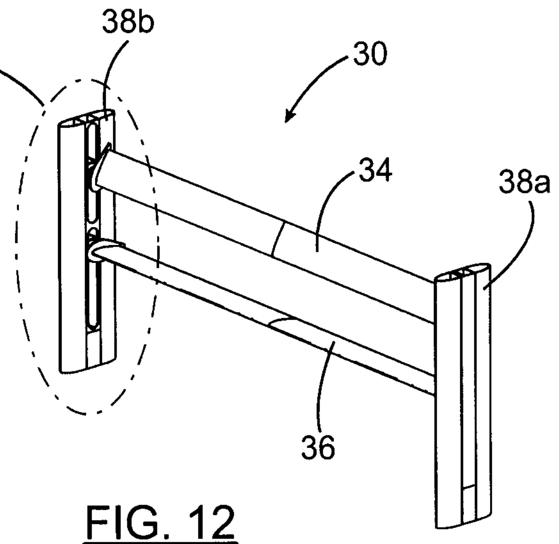
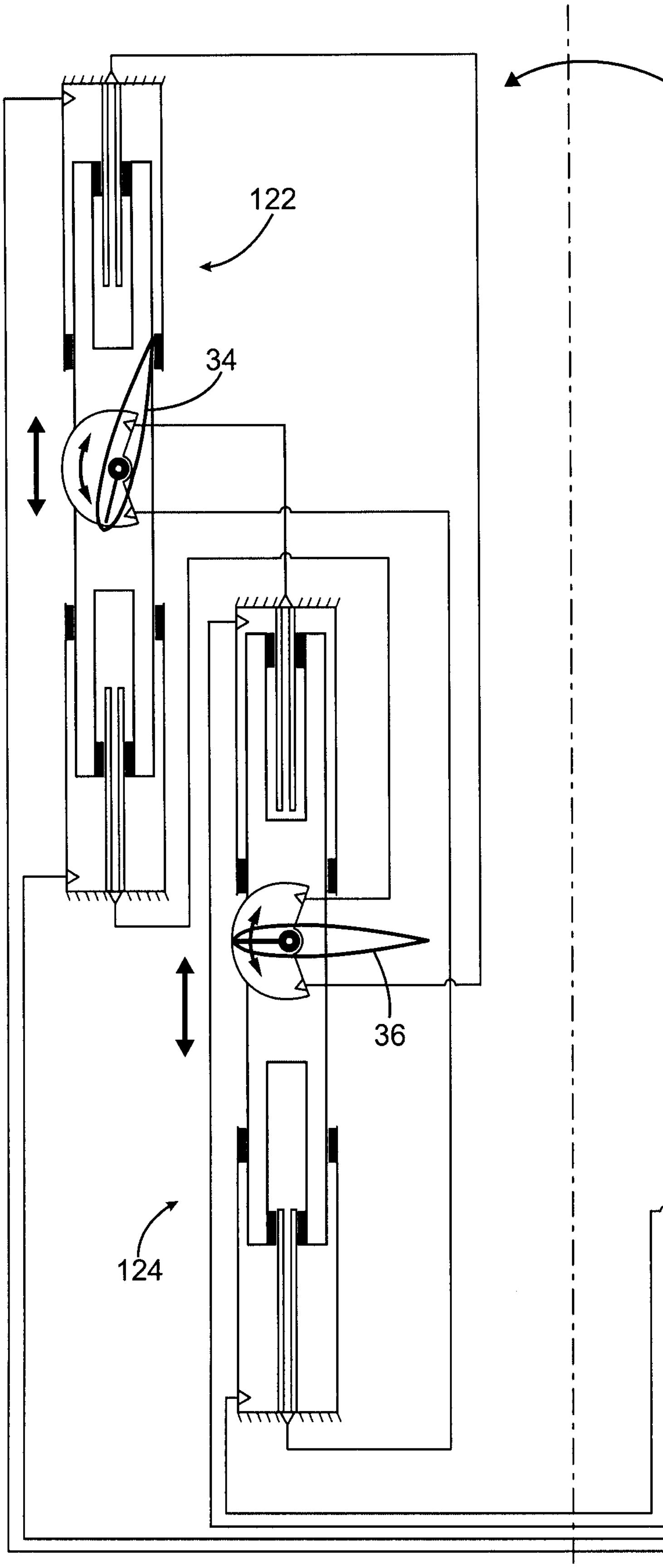


FIG. 12



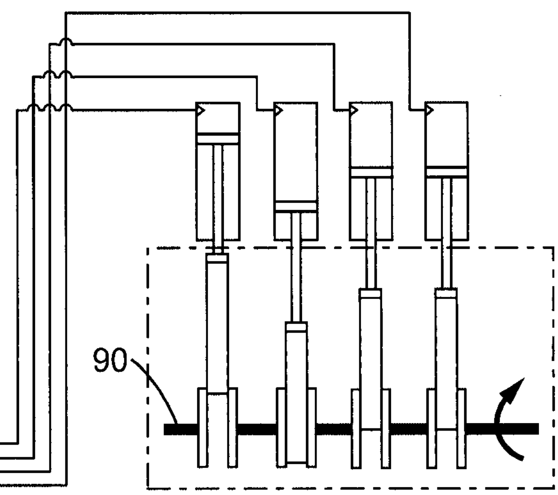


FIG. 12A

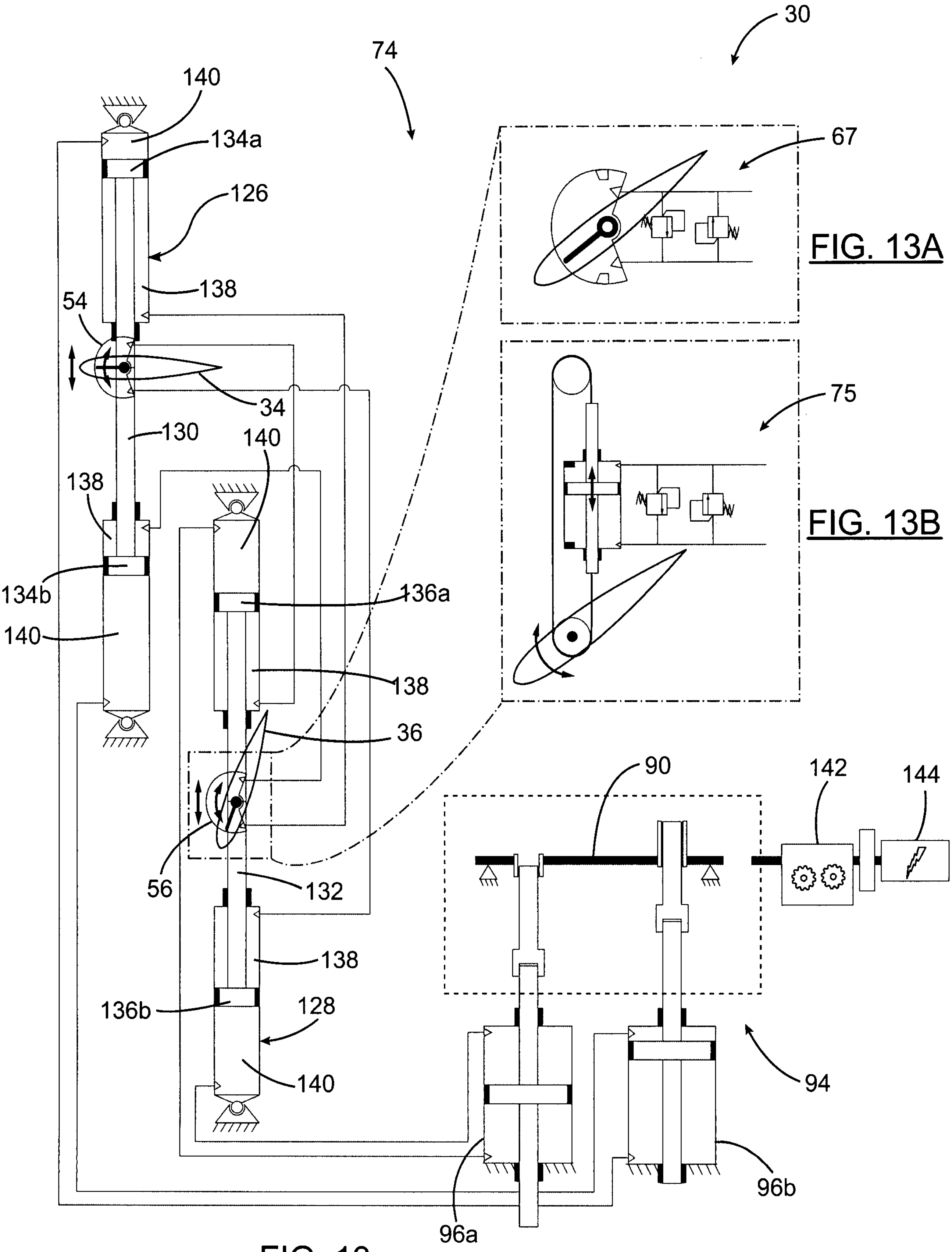


FIG. 13A

FIG. 13B

FIG. 13

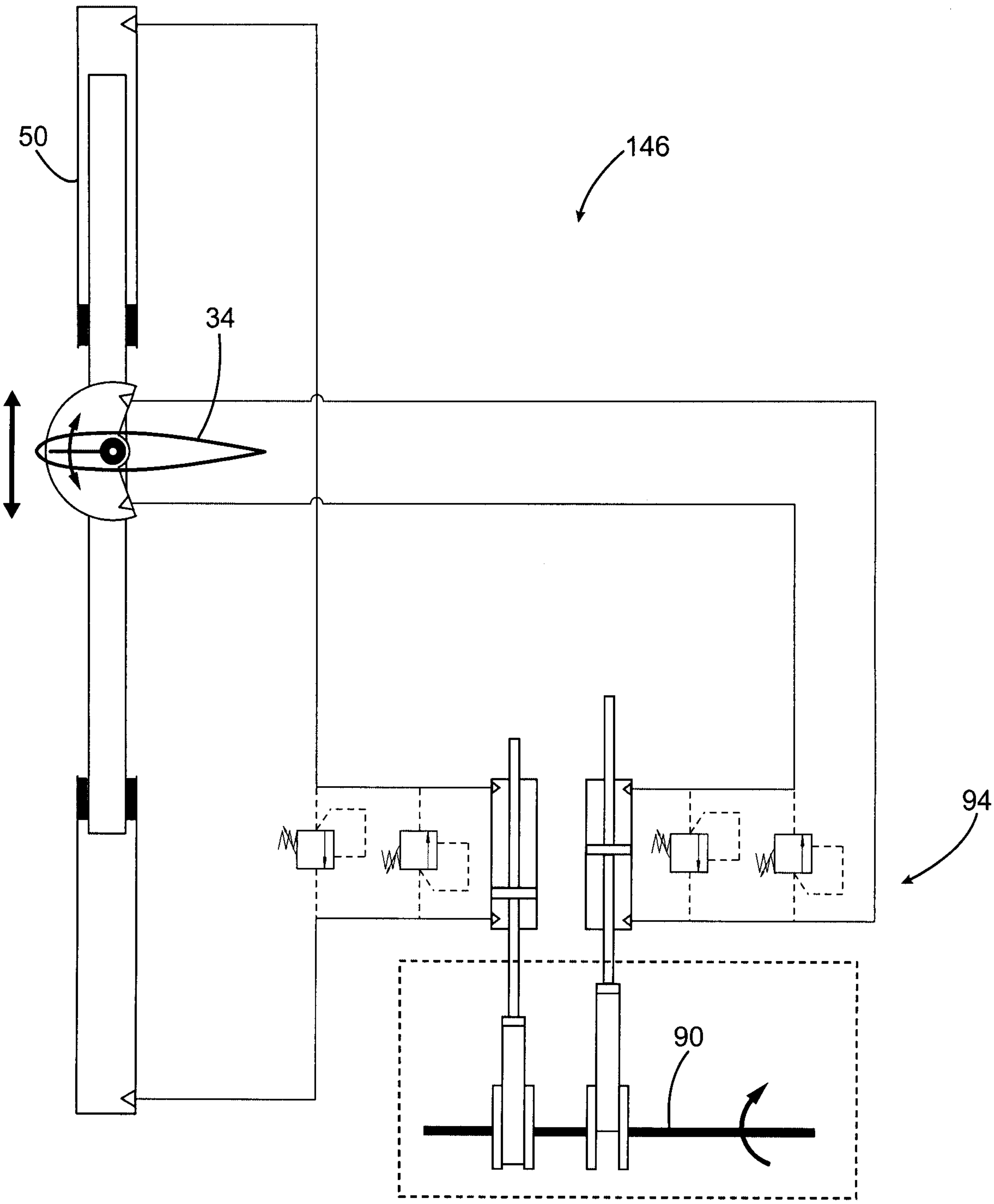


FIG. 14

INTERNATIONAL SEARCH REPORT

International application No.
PCT/CA201 1/001 107

A. CLASSIFICATION OF SUBJECT MATTER
IPC: ***F03B 1 7/06*** (2006.01) , ***F01D 23/00*** (2006.01) , ***F03B 13/12*** (2006.01) , ***F03D 5/06*** (2006.01)
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation seaixhed (classification system followed by classification symbols)
IPC (2006.01): *F03B 17/06 , F01I) 23/00, F03B 13/12 , F03D 5/06 , F03B 17/00*

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

Electronic database(s) consulted during the international search (name of database(s) and, where practicable, search terms used)
EPOQIJE (Epodoc), Canadian Patent database, Google Patent
Keywords: foil?, hydrofoil?, wing?, phase, pitch+, hydrokmetic

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category'*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	GB2412143 A (GRTNSTED, T. et al.), 2 1 September 2005 (21-09-2005) * Fig. 4 *	31 to 35
A	US2009121490 A1 (PLATZER, M. et al.), 14 May 2009 (14-05-2009) *whole document*	1 to 30
A	W09812433 A1 (ARNOLD, L.), 26 March 1998 (26-03-1998) *whole document*	1 to 30
A	WO2006055393 A2 (BERNITSAS, M. et al.), 26 May 2006 (26-05-2006) *whole document*	1 to 30

[ ] Further documents are listed in the continuation of Box C. [X] See patent family annex.

* Special categories of cited documents :
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority clami(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"Y" later document published after the international filing date or priority date and not m conflict with the application but citecTto understand the principle or theorv underlying the invention
"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
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined rath one or more other such documents, such combination being obvious to a person skilled m the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
10 November 201 l (10-1 1-201 1)	30 November 2011 (30-1 1-20 1l)

Name and mailing address of the ISA/CA
Canadian Intellectual Property Office
Place du Portage I, C114 - 1st Floor, Box PCT
50 Victoria Street
Gatineau, Quebec K1A 0C9
Facsimile No.: 001-819-953-2476

Authorized officer
Christine Lord (819) 953-1620

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of the first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons :

1. [ ] Claim Nos. :
because they relate to subject matter not required to be searched by this Authority, namely :

2. [ ] Claim Nos. :
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically :

3. [ ] Claim Nos. :
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows :

Group A: claims 1 to 30 are directed to a turbine, propulsive system and method for converting kinetic energy from a fluid flow to mechanical energy comprising a first and second hydrofoils each able to heave and pitch out of phase with respect to each other;

Group B: claims 31 to 35 are directed to a hydrofoil comprising a pair of foils connected via rigid links.

1. [ ] As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. [X] As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.

3. [ ] As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claim Nos. :

4. [ ] No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claim Nos. :

Remark on Protest [ ] The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

[ ] The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

[ ] No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/CA2011/001107

Patent document Cited in Search report	Publication Date	Patent Family Member(s)	Publication Date
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