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Transients analysis of a tidal currents self-balancing kinetic turbine with on shore basement

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Abstract

The aim of increasing the share of renewable energy sources to the total energy production has brought a significant increase of the interest in marine energies over the last years. Within them, tidal currents resources have been gaining ground for their advantages in terms of predictability, nonexistence of extreme flows, high load factor, minimal land occupation and visual impact. The authors, working in this field since many years, have been designing a new turbine able to work in the water like a kite, with no support structures, but easily connected to the coast by a rope. The constructive easiness, together with lower installation costs, are the main machine characteristics. Moreover it is able to overturn itself when the tidal current changes direction. The turbine equilibrium and mainly the transients related to the sink and surface phases, machine overturning, represent a critical aspect of the design. In the present work, starting from a phenomenological analysis, a simulation of the transients has been carried out in Simulink® environment. The study, related to the center of gravity, has pointed out the importance of the correct floating stabilizer design which helps the turbine to reach the equilibrium conditions even in case of flow instability.

Keywords: Marine Turbine; Transients analysis; Equilibrium conditions; Simulations in Simulink environment.

Nomenclature

b	viscous damping coefficient
L_{rope}	maximum length of the rope
L_{rod}	length of the rod
l_T	length of the stabilizer-turbine connector
m	turbine mass

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r_S	stabilizer radius
r_T	turbine radius
V_T	total volume of the turbine
α	empty/full ratio
ρ	water density
ρ_m	material density

1. Introduction

The tidal stream energy is an emerging form of renewable energy which, unlike many other ones, is a huge source of kinetic energy due to the regular tidal cycles influenced by the moon phases [1-4]. Intermittency is a problem for wind, wave and solar power since the sun doesn't always shine and the wind doesn't always blow. These renewable energy sources often require a backup from traditional forms of power generation. However, the inherent predictability of tidal power is highly attractive for grid management, avoiding the backup mostly powered by fossil fuel plants [5-7]. The tidal turbines can be installed on the seabed where high velocities or strong continuous ocean currents are available, and draw energy from the water flow.

A key point of each project is the ability to reduce the installation costs so that the plant quickly begins profitable. The machines actually working by tidal currents are moored to floating structures, or a wide supporting pylons like the Kobold [8], Darreius [9], Cormat [10], Seagen [11] turbines. Recently, hydrokinetic turbines [12] are gaining ground thanks to their simpleness.

The Unical-Sintenergy team deals with these issues for several years and, in addition to an international patent, has produced several scientific works [13-19]. The turbine developed by the authors is very simple because it does not need any bulky infrastructure: it is connected to the coast by a steel rope and works like a kite. The turbine works with bidirectional flows, being the installation suitable in sites where periodic inversion of the tides occurs. This possibility is offered by the particular connection to the ground: a special device, implemented in the machine, overturns it when tidal inversion occurs. During the positioning phases, useful to place the machine in the sea, in order to start the energy production, some transients happen. The geometrical parameters have to be chosen so that the turbine can sink and surface in the right way.

2. Functional turbine pattern

The turbine, see figgs. 1 and 2, has been widely described in previous works [13-19]. To briefly describe, it is set up by a double rotor, a deflector installed in the middle of the blade disc, a floating stabilizer, a built in generator, a frame whose a steel rope is connected, a rigid rod hinged to the coast. The working principle is quite similar to a kite: the rate of change of

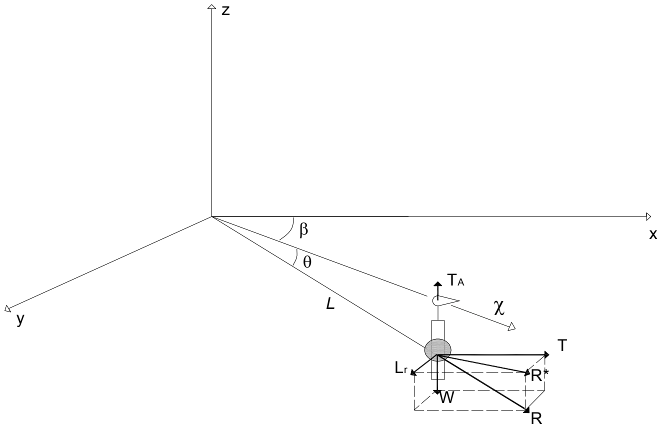

Fig. 1 Tridimensional view

the axial momentum (T) is balanced by the lift force (L_r) produced by the tidal current over the central deflector. The resultant force (R^*) stretches the rope and moves the turbine to an equilibrium position which, in the xy plane, doesn't change when the tidal velocity changes. This position depends only on the geometrical turbine configuration and it is characterized by the angle β [13-19]. As explained before, the machine operations are deployed as: working conditions and transient phases. In the next section a phenomenological analysis is described.

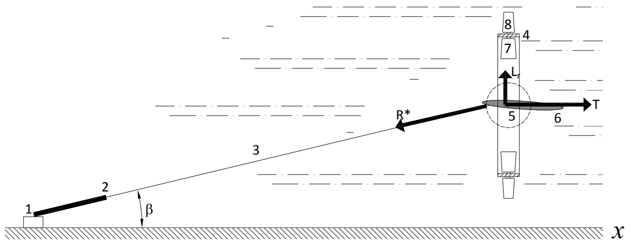

Fig. 2 Top view

	Key				
1	hinge	4	stator	7	internal rotor
2	rod	5	stabilizer	8	external rotor
3	rope	6	deflector	β	attack angle
L_r	lift	T	drag	R^*	horizontal resultant
W	weight	T_A	Arch. thrust	R	resultant

3. Phenomenological analysis of transients

The machine, thanks to a special device, is able to manage its movements during the transient phases. The rope is subjected to a load equal to the drag force applied to the turbine, so, in order to balance the drag, a counterweight has been introduced running coaxially to the rod. A hoist is connected to the rope making possible any counterweight positions, following the same rules of the turbine configuration. The transient phases can be split in: positioning in the sea, machine startup – power production, rope rewinding, tidal current direction change.

3.1. Positioning in the sea

At the beginning the turbine is connected to the rod, at position 1, floating thanks to the stabilizer immersed for a half part (fig. 3), as long as the current velocity reaches the right value able to produce a thrust T_r , greater than the one due to a counterweight installed in the rod. When the drag begins growing up, the rope rolls out towards the sea side. Now the machine, and the stabilizer too, leaves the rod and begins to sink, along the rod direction with an angle θ (see positions 1, 2, 3 of fig. 3). While the rope gradually unrolls, the machine sinks and pulls down the stabilizer, which produces an Archimedes' thrust gradually increasing, avoiding any sudden sinking. By the way, the machine becomes less heavy as long as it sinks and the angle θ reduces as shown in fig. 3. During this phase the β_1 angle (between the rope and the coast) doesn't change till the rope is completely unrolled (see fig. 4). Finally, the stabilizer will be more immersed producing the maximum Archimedes' thrust.

3.2. Machine startup - power production

When the current velocity (position 3 of figs. 3 and 4, machine startup) becomes equal to the machine startup one ($v_{startup}$), the dragging thrust T_t is replaced by the T_r one, due to the blades rotation (the values can be evaluated with the Betz theory) [20-21]. The power production starts at position 4 and the angle changes from β_1 to β_2 (see fig. 4). This angle won't change during the working phase [13-19] because it depends only on the machine geometric parameters.

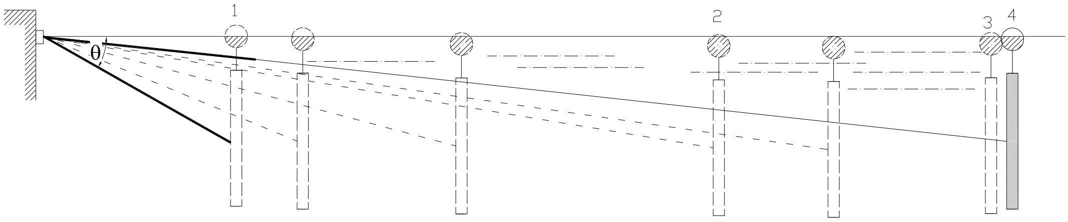

Fig 3 Operations during the transients – front view

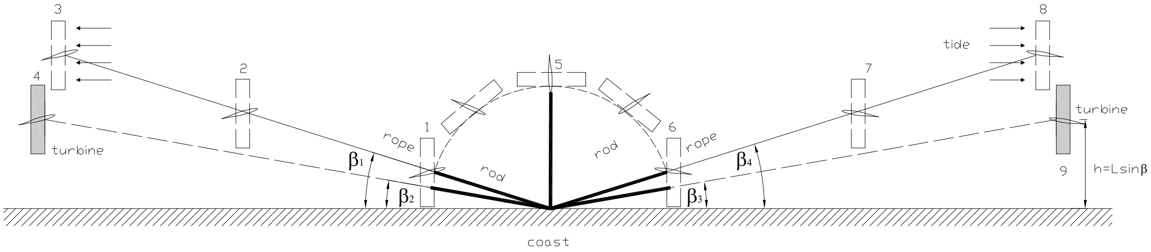

Fig. 4 Operations during the transients – top view

The machine reaches the equilibrium position: its coordinates (x, y) – see fig. 1 – don't change during this phase. It is important to highlight that the force T_r, due to the blade rotation, grows up as long as the tidal current, reducing the angle θ (fig. 3); consequently the machine begins quickly to surface, changing the z coordinate: meanwhile the stabilizer Archimedes' thrust opposes it, so the surfacing, in a short time, reduces its speed.

3.3. Rewinding of the rope

When the flow velocity reduces under certain values, the rope is rolled by the implemented counterweight fixture. The counterweight runs along the rod towards the sea, the machine, thanks to the rope, begins to move back to the coast. The turbine, moving through the positions 3, 2, 1 (see fig. 4), hooks the rigid rod linked to the coast by a hinge.

3.4. Tidal current direction change

When the tidal current changes its direction a machine rotation of 180° is requested in order to have the same side facing the flow: the rod rotates around the hinge, following the flow which drags the machine on the same direction. The machine gets through the positions 1, 5, 6 (fig. 4). Later, the positioning phase has to be repeated (the machine gets through the positions 6, 7, 8, with a β_4 angle symmetrical to β_1) and also the startup phase (the machine is in position 9 and starts its production). It is important to highlight that, during the machine overturn, the central deflector rotates around its axis of an angle equal two times the attach angle, getting the right position in a new working condition (see fig. 4). The fixture follows the machine in its behaviour, except the positioning phases in both sides of the mooring, which moves in two exact positions, due to the design parameters and the chosen site characteristics (positions 4 and 9, fig. 4).

4. Differential equations implementation

The differential equations, related to the different phases, can be obtained by considering the action of four different forces: the resultant R^*, which depends on the current velocity, and it is the sum of the rate of change of the axial momentum T and the lift force L_r , the Archimedes' thrust T_A of the stabilizer, the machine net weight W (the Archimedes' thrust of the full and the empty volumes not considered) and the counterweight action on the rope C_w. In fig. 5 a pattern, highlighting these forces in the vertical plane χz, containing the rope, is shown. During the first transient, the turbine start to sink. The initial condition are obtained considering the machine floating thanks to the stabilizer. The machine net weight is:

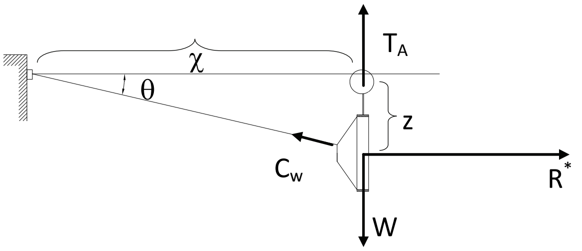

Fig. 5 Acting forces pattern

$$W = gV_T\left(\rho_m \alpha - \rho\right) \tag{1}$$

while the Archimedes' thrust is given by the action of the spherical cap:

$$T_A = g\rho\pi(z - r_T - l_T)^2 \left(r_S - \frac{z - r_T - l_T}{3} \right) \tag{2}$$

The initial value of the center of gravity z_o is given by the condition $W = T_A$, while the initial angle θ_o is given by:

$$\sin\theta_o = \frac{z_o}{L_{rod}} \tag{3}$$

During the first transient, related to the positioning in the sea, when the rope is still unrolling and its length is less than the maximum value L_{rope} , the dynamic equilibrium is given by the following equations:

$$\frac{m\chi^2\ddot{\theta}}{\cos^2\theta} + \frac{b\chi^2\dot{\theta}\sin^2\theta}{\cos^2\theta} = \left(R^* - C_W\cos\theta\right)z - (W - T_A)\,\chi \tag{4}$$

$$m\ddot{\chi} + b\dot{\chi} = R^* - C_W\cos\theta \tag{5}$$

$$z = \chi\, tg\theta \tag{6}$$

When the rope is completely unrolled the motion along the χ axis stops: the machine is now in the right position and begins to work. The path is an arc of a very small circle compared to the rope length: the motion is nearly vertical along the z axis. The differential equations, related to this second transient (power production), are:

$$mL_{rope}^2\ddot{\theta} + bL_{rope}^2\dot{\theta} = R^*\sin\theta\, L_{rope} - (W - T_A)\cos\theta\, L_{rope} \tag{7}$$

$$\chi = L_{rope}\cos\theta \tag{8}$$

$$z = L_{rope}\sin\theta \tag{9}$$

The differential equations related to the rewinding rope transient are the same as the first transient (positioning in the sea – eqq. 4, 5, 6) taking into account the different initial conditions, i. e. the initial turbine velocity considered equal to zero (the values are really small, near to zero) and the initial position χ equal to the $L_{rope} \cos\theta$, where the value of θ is given by matching the drag force T and the horizontal component of the counterweight C_w responsible of the rope rewinding.

When the tidal current inversion occurs the turbine turns itself and the two transient, positioning in the sea and power production, start over in the same way but in opposite side.

5. Results

The previous differential equations have been implemented in Simulink environment. The simulation is referred to a machine diameter of 12 m working in a tide stream flow with a current velocity of 3 m/s. The machine mass have been estimated on 22500 kg, while its net weight, by considering the empty/full ratio α equal to 0.5, is 4500 kg (see eq. 1). In this condition a spherical stabilizer with a radius of 1.3 m is able to manage the transient phases and guarantees an expected and regular motion in the sea. In the initial position the stabilizer is half immersed.

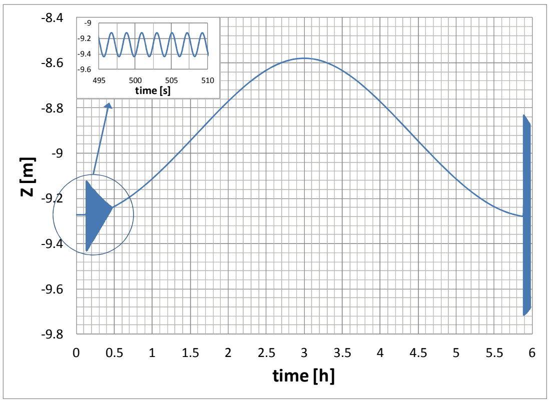

Fig. 6 Variation of the vertical position z of the center of gravity

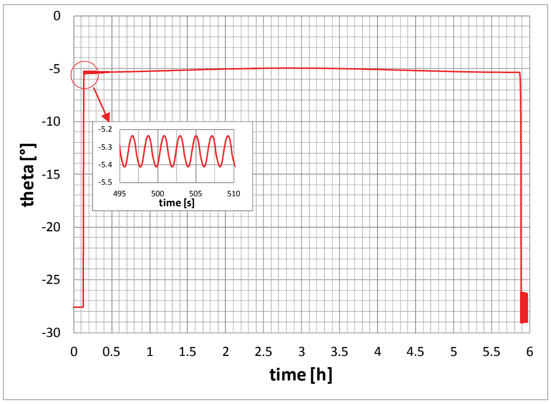

Fig. 7 Variation of the sinking angle θ as function of the time

The main simulation results can be synthesized in: variation of the vertical position z of the center of gravity, variation of the sinking angle θ, as function of the time (see figgs. 6 and 7).

At the beginning the center of gravity, supposed in the middle of the turbine, is 9 m below the sea surface, and the θ angle (see fig. 2 and 4) of the rod is – 27°. After about 8 minutes the tidal velocity grows so much that the resultant R^* exceeds the counterweight and the machine starts to approach the sea. The approach comes gradually and the center of gravity doesn't change its vertical position (small variations of a few centimeters). After about a minute the rope is completely unrolled and the turbine is located at position 4 of fig. 4: the machine cannot move horizontally and some oscillations occur with a maximum amplitude of 10 cm and frequency of 0.2 Hz, which dampen in about 20 minutes (see fig. 6). The fluctuation of the θ angle, related to the first transient, is about 22°: the oscillations are displayed in fig. 7.

At this point the second transient starts (power production) and the center of gravity follows a circular path raising on the top. The vertical machine fluctuation during this second transient is about 70 cm, while the θ angle changes maintaining values around - 5°. The evolutions of the vertical position z and the θ angle follow the tide variation: the stabilizer doesn't completely surface but, at the peak of the z position, is still immersed for 60 cm. When the tide reduces, the resultant R^* decreases and the motion reverts: the machine drops following the same circular arc until the maximum sinking. When the value of the resultant R^* becomes lower than the counterweight, the machine, thanks to the rope, begins to withdraw to the coast. The differential equations managing this transient are the same as the ones of the first transient (eqq. 4, 5, 6), but the initial conditions are different.

Finally, the machine meets the rod and it is forced to stop producing some relevant oscillations with a maximum amplitude of about 0.5 m which dampen in a certain time (see figgs. 6 and 7).

6. Conclusions

The simulation of the transients, related to the different working phases of a tide self balancing turbine, has been done in Simulink environment: this is a first step, carried out in an ideal situation. Further simulations are in progress considering different startup conditions, in order to deeply define all the transient phases. Anyway the calculus has been able to fix the right ratio empty/full of the turbine volumes as well as the size of the floating stabilizer. The results show the turbine, during the positioning phase, sinks by a small vertical center of gravity change: when the rope is unrolled it gradually surfaces thanks to the action of the floating stabilizer. The simulation shows some critical features at the end of the last transient (rewind of the rope), when the turbine hooks the rod and some relevant oscillations occur in the vertical direction. The rough hooking action could be corrected implementing a damper in the rod system. The authors are studying the best way to realize the right rod-turbine connection.

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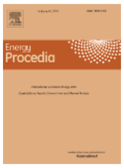
Biography



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