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Energy Procedia 142 (2017) 29–36

Energy Procedia

www.elsevier.com/locate/procedia

9th International Conference on Applied Energy, ICAE2017, 21-24 August 2017, Cardiff, UK

Innovative on-Shore System recovering Energy from Tidal Currents

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An innovative system for the recovering of energy from tidal currents is proposed. The system is composed of a blade submerged in sea waters and connected to a vertical bar which, moving up and down through the tide action, transfers energy to a double effect piston pump. The latter feeds a pressurized reservoir able to provide water flow rate, at a suitable pressure level, to a hydraulic turbine. The basic configuration involves a four-bar linkage connecting the vertical bar and the piston pump. The system can be easily employed in all those sites whose seabed quickly deepens and whose tidal currents are parallel to the coast. The proposed system is a valid alternative to the current tidal energy converters: its big dimensions are necessary to balance the low efficiencies of the overall energy conversion. At any rate, during the working the seabed is not altered, neither is the aquatic fauna damaged.

Keywords: Tidal [illegible] System; On Shore; Immerged Blade; Double Effect Piston Pump; Hydraulic Turbine.

[illegible]

A	swept area	[m^2]
A_s	piston area	[m^2]
B	blade length	[m]
C_A	friction torque	[Nm]
c_D	drag coefficient	[-]
C_I	torque of inertia	[Nm]

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10.1016/j.egypro.2017.12.006

C_L	lift coefficient of the blade	[-]
C_M	blade torque	[Nm]
C_R	resistant torque	[Nm]
c_R	resistant coefficient	[-]
C_W	weight torque	[Nm]
D	blade drag force	[N]
D_p	piston diameter	[m]
f	frequency	[Hz]
g	gravity	[m/s^2]
L	blade lift force	[N]
I_c	crank moment of inertia	[kg m^2]
I_s	crank-piston moment of inertia	[kg m^2]
P	pressure	[Pa]
R	blade resistant force	[N]
R_c	cranks length	[m]
R_I	decrement of the cranks length	[m]
R_{II}	increment of the blade distance	[m]
R_s	connecting crank length	[m]
m_{air}	air mass	[kg]
m_p	pump flow rate	[kg/s]
m_{res}	reservoir water mass	[kg]
m_t	turbine flow rate	[kg/s]
M_b	blade mass	[kg]
M_c	cranks mass	[kg]
M_s	connecting crank and piston mass	[kg]
Pow	power	[kW]
p_{res}	reservoir pressure	[bar]
$t_{half\text{-}cycle}$	half cycle time	[s]
T_{air}	air temperature	[k]
T	tide period	[h]
t	time	[h]
U	blade velocity	[m/s]
V	tidal velocity	[m/s]
V_o	peak tidal velocity	[m/s]
Vol_p	pump vo[illegible]e	[m^3]
Vol_{res}	reservo[illegible]e	[m^3]
W	relat[illegible]ocity	[m/s]
Z	vert[illegible]	[m]
α	angle between the lift force and the vertical direction	[°]
λ	aspect ratio of the blade	[-]
η_{El}	electrical efficiency	[-]
η_p	pump efficiency	[-]
η_{tot}	total efficiency	[-]
η_t	turbine efficiency	[-]
θ	crank angle	[°]

[illegible]

In a problematic worldwide energy scenario characterized more and more by the need to replace fossil fuel energy sources [1], present research lines are addressed toward renewable sources [2]. Among these, tidal currents are considered a perfectly predictable, but not yet fully exploited energy source of particular interest [3]. Often off-shore solutions, employing big stand-alone turbines or array turbines, are chosen [4]. This is the case of the Openhydro turbines [5], being developed in Nova Scotia (Canada) and in the Irish Sea, or of the Seagen turbines [6] being developed in the UK.

Other alternative systems are, for example:

- the Biostream device [7] which is an oscillating-hydrofoil made up of a foil linked to a mechanical arm actuating a hydraulic circuit, thanks to the lift force produced by tides;
- the tidal kite turbine [8], which is a turbine connected to a kite anchored to the seabed, potentially very efficient and operating at currents lower than 1.2 m/s;
- the Archimedes screw tidal turbine (Flumill solution) [9], generating electricity by means of the screw rotation.

However, the necessity to construct civil infrastructures in the open sea, and the maintenance operations involving skilled manpower imply high installation costs which discourage potential investors [10]. On the contrary, the systems conceived with the basement on-shore will be surely cheaper and can be easily installed [11]. The size of the frame to which to connect the turbines constitutes an important issue of these solutions: the frame has to be thin enough to avoid high visual impact but at the same time thick enough to support the sea thrusts [12].

For this reason a system whose mobile parts are completely immersed in water has been conceived. The turbine [13] has been replaced by a simple blade profile moving alternately up and down under the tide effect, able to support the acting forces. The alternate motion can be converted into pressure energy by a double effect piston pump, which feeds a pressurized reservoir. Finally, a hydraulic turbine, connected to an electric generator, receives water under pressure from the reservoir.

In this [illegible] architecture of the proposed system together with its main features.

[illegible]

The original purpose was to create a system able to catch energy from the tides flowing parallel to the coast by means of a simple profile like a pedal submerged in the sea near the coast, moving up and down in alternate motion, and to convert this alternate motion in the rotating motion of a turbine placed onshore. This system could resolve all the issues linked to the maintenance operations and cut the installation costs. The main advantage is to remove the group turbine-generator from the sea, anyway paying the price of lower efficiencies.

The vertical alternate motion can be transferred to ground by a four-bar linkage useful to actuate a piston pump, which delivers pressurized water to a reservoir filled partly with water and partly with air. A hydraulic turbine receives the water flow circulating in a closed circuit: in fact, the flow is discharged in a tank but it is successively re-pumped into the reservoir by the piston pump.

Figure 1 shows the system configuration highlighting the various components: the blade, the four-bar linkage, the double effect piston pump, the pressurized reservoir, and finally the turbine-generator group.

The pressure level of the reservoir changes according to the tidal current velocities variations, which determine the entity of the lift thrust acting on the immerged blade and so the consequent action of the piston pump.

The hydraulic blade profile is conceived as moving up and down like a pedal under the lift thrust of the tide itself, with the possibility of changing its inclination as shown in the detail of Fig. 1. This change helps the profile to move up and down b[illegible]n changes in accordance. For this purpose, the profile is chosen symmetrical.

[illegible]

With the aim to calculate the equations related to the blade motion, the dynamic equilibrium is considered. The acting moments with respect to the crank hinge are the following: torque C_M generated by the lift force acting on the blade; resistant torque C_R generated by the water pressure on the piston pump; friction torque C_A due to the drag force acting on the blade in the vertical direction; weight torque C_W due to the weight of the elements involved in the vertical motion of the blade; torque of inertia C_I proportional to the inertia of the system.

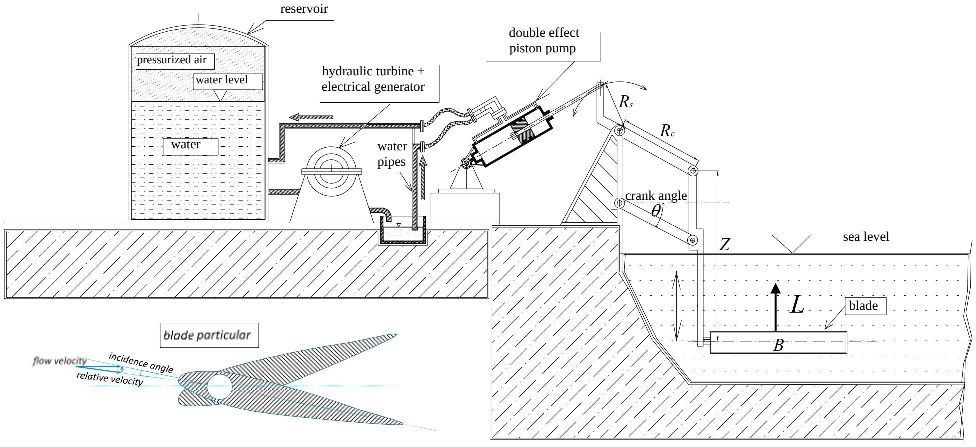


Fig. 1. System configuration and blade particular.

The motion equation is [14]:

$$C_I = C_M - C_R - C_A - C_W \tag{1}$$

In order to obtain the time evaluation of the various quantities (angle, velocity, power, etc.), the above described torques have been written as function of the crank angle *(θ)*.

As shown in Fig. 1, the blade profile, invested by the tidal current of velocity V, moves toward the top with velocity U. The thrusts of lift (L), drag (D) and resistance (R) of the blade profile are given by the following equations [15]:

$$L = \frac{1}{2}\rho W^2 c_L \frac{B^2}{\lambda}; \quad D = \frac{1}{2}\rho W^2 c_D \frac{B^2}{\lambda}; \quad R = \frac{1}{2}\rho U^2 c_R \frac{B^2}{\lambda} \tag{2}$$

The various torques with respect to the cranks hinge are defined as:

$$C_M = L\cos\alpha\left(\frac{B}{2} + R_c\cos(\theta)\right); \quad C_R = pA_sR_s; \quad C_A = R\left(\frac{B}{2} + R_c\cos(\theta)\right); \quad C_W = gM_cR_c\cos(\theta) \tag{3}$$

While the total torque of inertia, by considering the inertia of the various components, is given by:

$$C_I = \left[2I_c + I_s + (M_c(R_c - R_I) + M_b(R_c + R_{II}))R_m + M_sR_s^2\right]\ddot{\vartheta} \tag{4}$$

The signs of the torques change according to the direction of the blade: when it goes up the signs are those of eq. 1 except the last part of the vertical path when the blade changes inclination for braking before reaching the top and, consequently, the torque C_M changes sign. The opposite happens when the blade goes down except for the weight torque C_W that is always negative.

All the above described formulas have been implemented in a software developed in Simulink® environment, taking into account the first sizing of the system considering a squared blade (B) of 8 m, a vertical bar (Z) of 9 m, a piston pump diameter (D_p) of 0.25 m and maximum theta oscillations of ± 25°. The masses considered are: blade mass (M_b) of 1096 kg with a net weight in water of zero, cranks mass (M_c) of 850 kg, connecting crank and piston mass (M_s) of 355 kg. In the next figures, some outputs of the software are reported. Figure 2 shows the crank angle and the attack blade angle oscillations by considering a pressure of the reservoir of 4 Bar and a tidal velocity of 1.5 m/s.

Fig. 3 instead shows the trend of the various torques acting on the system in relation to a complete cycle, by considering a pressure of the reservoir equal to 9 Bar and a tidal velocity of 2 m/s.

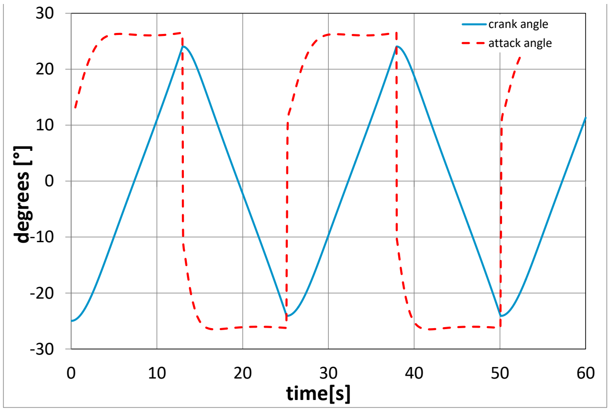


Fig. 2 Crank and a[illegible] angles [illegible]llations – reservoir pressure [illegible] Bar, tid[illegible]ocity = 1[illegible] m/s.

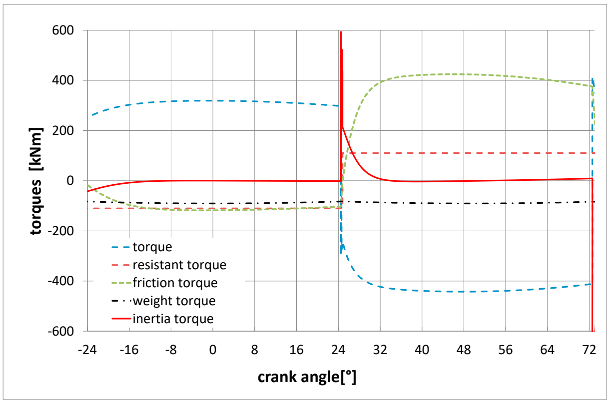


Fig. 3 Torques trend by changing the crank angle – reservoir pressure of 9 Bar, tidal velocity = 2 m/s.

The performances of the system are determined by the tidal current velocity: in fact, when the tide rises the oscillations frequency of the mobile parts increases and consequently the power and the efficiency of the system increase. However, with the aim to maintain high efficiencies, the reservoir needs always-higher pressures that imply lower frequencies. The work done in a cycle is higher as much as the pressure grows, but the power is obviously linked to the time in which this work is done. There will be an optimal value of the resistant torque, and, for an assigned geometry of the various components, of the reservoir pressure, for any tidal current velocity value.

This occurrence can be focused by evaluating the overall efficiency of the system starting from the flowing energy of the current through the vertical area swept by the blade profile, expressed as:

$$A = 2BR_c \sin(\theta_{max}) \tag{5}$$

Taking into account the energy flowing across the transversal area A above defined and the overall efficiency η_{tot}, the power of the system is simply given by the following equation:

$$Pow = \eta_{tot} \frac{1}{2} \rho V^3 A \tag{6}$$

Unfortunately, the overall efficiency is not immediately calculable. The efficiency is defined as the energy supplied by the electrical generator in a half cycle on the energy flowing through the swept area A in the same time ($t_{half\text{-}cycle}$). By considering that the energy supplied by the generator is equal to the pressure energy pumped by the piston pump [16], whose volume is indicated as Vol, and taking into account the pump efficiency η_P, the turbine efficiency η_T and finally the generator efficiency η_{El}, the following expression is proposed:

$$\eta_{tot} = \frac{\eta_{El}\eta_P\eta_T p_{res} \cdot Vol}{1/2\rho V^3 A t_{half-cycle}} = \frac{4\eta_{El}\eta_P\eta_T p_{res} \cdot Vol}{\rho V^3 A} f \tag{7}$$

where f is the frequency of the moving blade and p_{res} the pressure of the reservoir. The frequency f depends on different factors: the various torques involved as well as the overall inertia of the system. It can be calculated by means of the software implemented in Simulink whose equations have been illustrated previously.

The first analysis of the system can be done by considering constant the various efficiencies involved in eq. 7 (η_{El}, η_P, η_T) by assuming values traditionally adopted for them.

So an electrical efficiency of *90%,* a pump efficiency of *85%,* and finally a turbine efficiency of *85%,* are assumed. Particularly the latter value is true under the hypothesis when considering a Pelton turbine working at variable rotational speed, so that the efficiency is always at the maximum value.

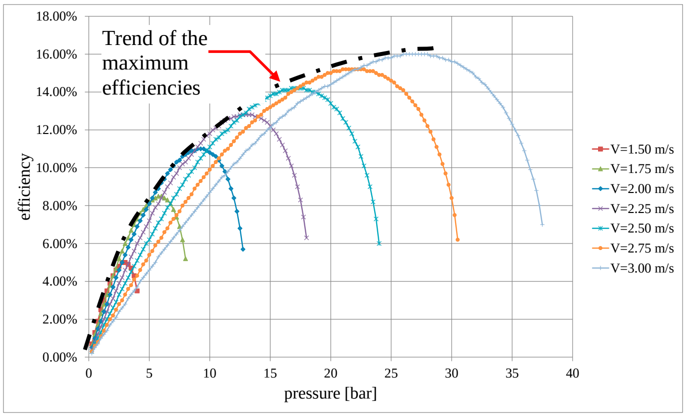


Fig. 4 Efficiencies curves of the system by changing the tidal velocities, the system frequency and the pressure of the reservoir.

Figure 4 reports the efficiency curves, and the reservoir pressure of the system by changing the tidal current velocity from 1.5 m/s to 3 m/s. The maximum values of efficiency follow a trend highlight by the dashed line: they are obtained for particular values of pressure and velocity. By assigned a piston pump diameter (D_p) of 0.25 m, the following correlation involving these quantities is found:

$$p_{res}= 3.6\ V^2 - 0.16\ V - 4.88 \tag{8}$$

Obviously, for maintaining the pressure to the optimized values, a control strategy is required which is described as it follows.

4.1. Control strategy

The pressure control is done by changing the flow rate feeding the turbine. The reservoir receives a flow rate at each cycle provided by the pump equal to the product of its delivered volume and to the system frequency.

$$\dot{m}_p = \rho Vol_p \cdot f \tag{9}$$

The quantity of mass accumulated in the reservoir instead can be calculated as it follows

$$\frac{\Delta m_{res}}{\Delta t_{cycle}} = \rho\left(Vol_{res} - \frac{m_{air}\bar{R}T_{air}}{p_{res}}\right)/\Delta t_{cycle} \tag{10}$$

where the pressure p_{res} is provided by eq. 7.

By considering a half tidal cycle of 6 hours with a sinusoidal trend as:

$$V = V_o \sin\left(\frac{2\pi}{T}t\right) \tag{11}$$

with T equal to 12 hours and V_o equal to 3m/s, and considering moreover a reservoir of 16 m^3 pressurized with a mass of air of 50 kg, taking into account equations 7 and 10, it is possible to calculate the water mass accumulated in the reservoir which results:

$$\frac{dm_{res}}{dt} = \rho\frac{m_{air}\bar{R}T_{air}\left[16.96\sin\left(\frac{\pi}{3}t\right) - 0.254\cos\left(\frac{\pi}{6}t\right)\right]}{\left[32.4\sin^2\left(\frac{\pi}{6}t\right) - 0.486\sin\left(\frac{\pi}{6}t\right) - 4.88\right]^2} \tag{12}$$

The flow rate delivered to the turbine is then calculable as the flow rate provided by the pump deducted by the water mass accumulated in the reservoir, i. e.:

$$\dot{m}_t = \dot{m}_p - \frac{dm_{res}}{dt} \tag{13}$$

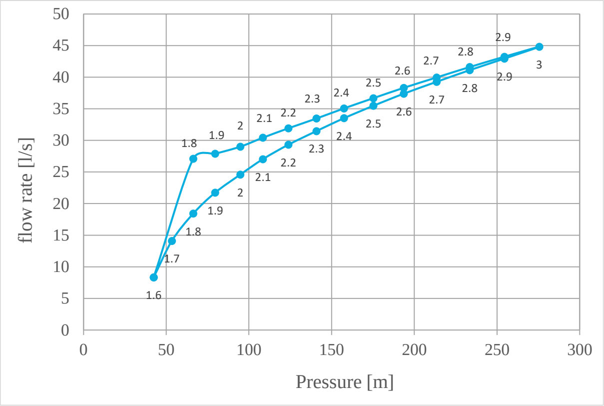
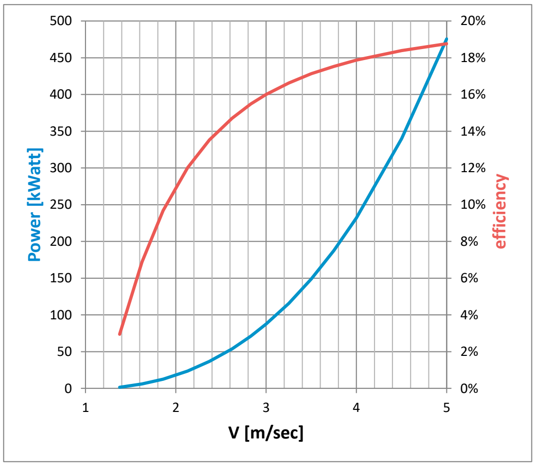


Fig. 5 Pressure and flow rate changes of the turbine by varying the tidal velocity

Figure 5 illustrated the optimized pressure and flow rate changes during a half cycle of tide with maximum peak velocity of 3 m/s: the pressure is expressed in meters of water column and the flow rate in litres per second. The tidal velocities are overlapped on the bullet points of the graph. When the tidal velocity increases, the pressure of the reservoir augments until 275 m, while the flow rate augments until 45 l/s. When the tidal velocity decreases, the pressure of the reservoir decreases until 40 m but in this case the flow rate feeding the turbine is higher because of the delivering of the accumulated mass (see eqq. 9 and 12).

Figure 6 shows how the efficiency and the power of the system, optimized by a system control pressure, change with the tidal current velocity. The efficiency increases by augmenting the tidal velocity and the higher values approach the limit of 20%. The power reaches interesting values, from 70 to 470 kW, in the range of 3÷5 m/s of tidal currents velocities.



[illegible]g. 6 Efficiency and Power of the system by changing the tidal velocities

The authors present a new system able to convert energy from tides flowing parallel to the coast by means of simple components placed directly onshore. This system is inspired by the recent “Oscillo Drive” technology [15], which is addressed instead to exploiting marine waves. That happens through point absorber buoys connected to a hydraulic circuit and, finally, to a turbine. In a similar way, the proposed system is equipped with a component, the blade profile, immersed in water, working efficiently to convert the lift thrust of the tidal current into electric energy. That happens by means of intermediate devices like four bar linkage, piston pump reservoir and hydraulic turbine.

The novelty of the present work is to offer a cheap, easily installable onshore solution in all those situations where the tidal current are parallel to the coast (straits, lagoons, estuaries and so on) and the seabed quickly drops with respect to the coast. The efficiency of the system is lower than a traditional turbine [18], but at the same time, the system is structurally more resistant and requires less maintenance and at a lower cost. It could be an interesting alternative to the present technol[illegible] exploiting tidal currents, involving onerous turbines immersed in the open sea, continuously worn out by th[illegible]

A new system collecting energy from sea currents has been proposed, which can be placed directly on the coast and which can be advantageously used in sites where the seabed drops rapidly from the coast.

The system is innovative because, operating directly on the coast, it aims to achieve installation costs lower than those of the systems placed in the depth of the sea. Of course, it does not fit all sites, as it is necessary that the sea current is significantly important near the coast. It is also particularly suitable for those sites in which the current changes cyclically since the mechanism that drives the blade adaptable to these changes and keeping the blade always in perfect alignment with respect to the current.

Simple preliminary estimates indicate that the system is able to supply electric power even with not excessively large dimensions and in sites where the currents are not significantly great. Moreover, it is designed in compliance with sa[illegible] environment and aquatic fauna.

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