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Design and numerical analysis of a double rotor turbine prototype operating in tidal currents

Silvio Barbarelli[a]*, Teresa Castiglione[a], Gaetano Florio[a], Nino Michele Scornaienchi[a], , Giacomo Lo Zupone[b]

[a]*Department of Mechanical, Energetic and Management Engineering University of Calabria, 87036 Rende, Italy*
[b]*SintEnergy srl –Reggio Calabria, Italy*

Abstract

This work shows the results of a study carried out for several years by the Department of Mechanical, Energy and Management Engineering (DIMEG), in collaboration with SintEnergy Srl. The aim was to develop an innovative marine turbine, taking advantages from the tidal currents. The turbine, which is made-up of two concentric contra-rotating rotors, has been designed to operate anchored to the coast without any supporting structures on the seabed. An iterative procedure, based on a zero-dimensional approach, was developed for the estimation of blades dimensions as well as the rotors performances in terms of lift, drag, power coefficient and efficiency. In order to validate the results of the design procedure, numerical simulations based on three-dimensional analysis were also carried out. The three dimensional study was carried out using the commercial code FLUENT, which follows the Reynolds Averaged Navier-Stokes (RANS) approach, in conjunction with the two-equation Realizable k- ε turbulence model.

Keywords: Turbine Prototype; Tidal Currents; Counter-Rotating Rotors; CFD Analysis of External Rotor.

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* Corresponding author. Tel.: +390984494650; fax: +390984494673.
E-mail address: silvio.barbarelli@unical.it

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Nomenclature

a_0	infinite foil lift curve slope
a	finite foil lift curve foil
A_1	external rotor area
A_2	internal rotor area
AR	foil aspect ratio
C_D	drag coefficient
$C_{D,th}$	theoretical value of the drag foil coefficient
$C_{D,sim}$	simulated value of the drag foil coefficient
C_L	lift coefficient
$C_{L,inf}$	infinite lift foil coefficient
$C_{L,th}$	theoretical value of the lift foil coefficient
$C_{L,sim}$	simulated value of the lift foil coefficient
C_p	power coefficient
C_{p1}	external rotor power coefficient
C_{p2}	internal rotor power coefficient
D_i	internal diameter
D_e	external diameter
E_p	foil efficiency
L_r	deflector lift
P	power machine
P_0	flow power
T_A	Archimedes' thrust
T	blades thrust
W	machine weight
λ	tip speed ratio
v_o	undisturbed tidal velocity
z	blades number
η_e	electrical efficiency
η_m	mechanical efficiency

1. Introduction

The actual research lines are concentrating on the local resources by favoring the approach of the smart systems [1-2]. Tidal currents represent a huge source of energy, which can be exploited also in proximity of the coast, better than the wind [3], by means of local on-shore installations. They have high density and are perfectly predictable due to the gravitational interaction earth-moon [4]. The main problem is represented by the very high initial costs, which discourage potential investors [5-6]: civil works in water are very difficult and long times are needed, special equipment, and skilled manpower.

The machines actually working in tidal currents like the Kobold [7], Cormat [8], Darreius [9], Seagen turbines [10], have a not competitive LCOE [5-6].

The authors present a new idea of marine turbine. The innovative machine concept is a turbine anchored to the coast just using a rope [11-12]: its operation is comparable to the one of a kite. This easy mooring concept allows to reduce the installation cost: no support structures are needed.

Once defined the turbine operation cycle, the anchoring system and the expected performances, the team Unical SintEnergy designed the first prototype in order to carry out some tests useful for validating the design algorithm.

In this work, a CFD analysis, involving the whole external rotor, has been performed with the aim to confirm the design choices.

2. Sintenergy Turbine

The SintEnergy turbine allows to collect energy from tidal currents (see fig. 1).

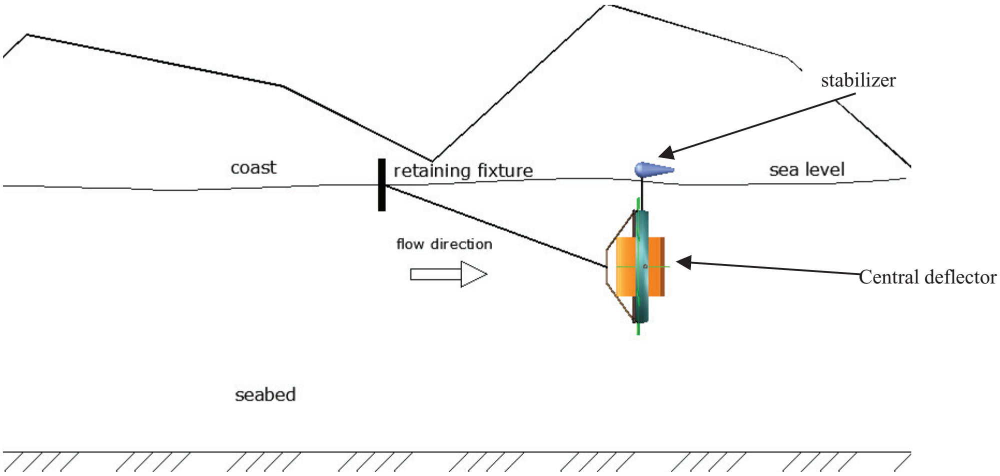

Fig. 1 Working scheme of the turbine.

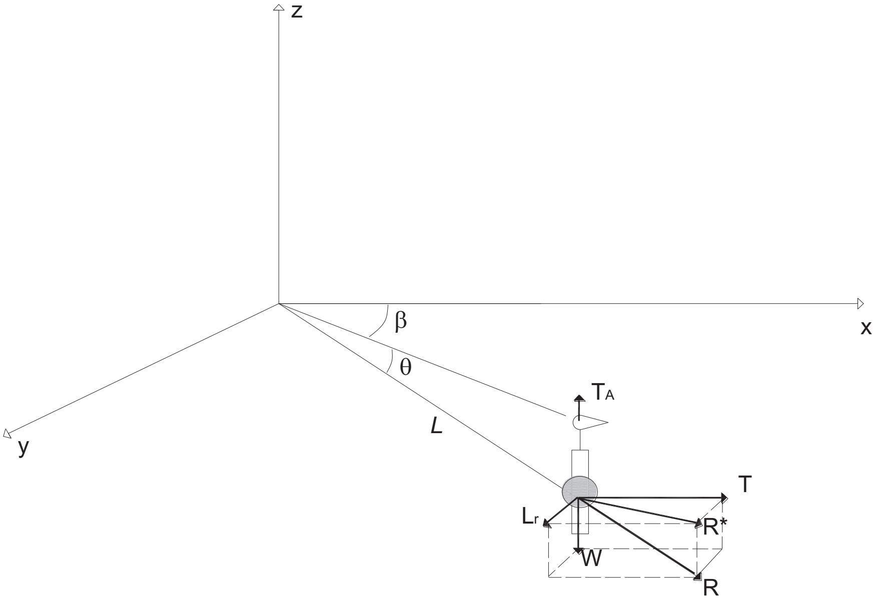

Fig. 2. Three-dimensional pattern.

The machine is based on two contra rotating rotors and a stator equipped with a built in permanent magnets generator (PMG). The rotors are sized having the same torque so that the turbine is free for any torsional effect. The two rotors turn producing energy, while a central deflector makes the machine always aligned to the flow [11-12] and a vertical stabilizer (a sort of buoy) maintains the machine at right depth [13].

The operating cycle can be simply described: as shown in figs. 1 and 2, the equilibrium is deployed in two plans.

The weight (*W*) – reduced by the Archimedes' thrust (T_A) – and the rate of change of the axial momentum (*T*) are balanced by the lift produced by the tidal current on the central deflector installed in the middle of the blade discs. This last force (L_r – see fig. 2) pushes off the turbine, but the simultaneous action of the forces *W*, T_A, *T* and of the reaction *(R)* of the rope, allows the turbine to reach the equilibrium in a position, related to the coast, which doesn't change when the flow velocity changes [11-12].

The turbine has to work in the tidal currents and that can represent an arduous problem. For this reason a special mechanism has been thought. The tides change direction twice a day, following an absolutely predictable sinusoidal trend due to the interaction earth-moon. When the tide changes direction, the machine has to be able to find a new position in the sea [13-14] and the following actions occur (Fig. 3):

- rewinding the rope, so that the turbine moves to the coast from its equilibrium position;
- rotating the whole machine when the current changes direction;
- releasing the rope, so that the turbine moves to the sea in a new equilibrium position.

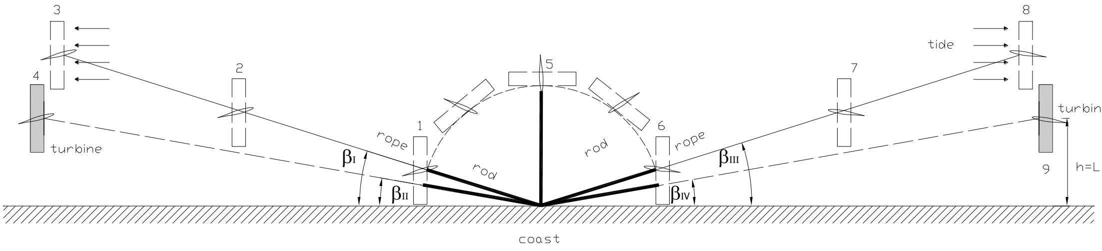

Fig. 3 Operations during the transients – top view

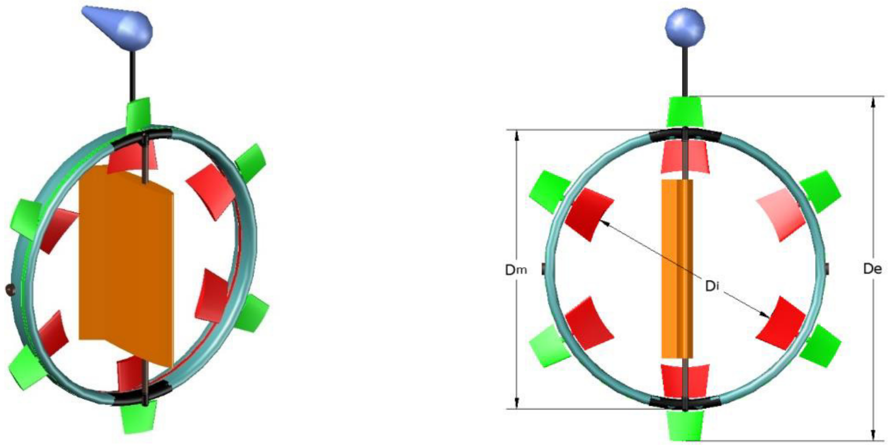

Fig. 4 The turbine prototype

Fig. 4 shows the turbine prototype: in the figure are visible the components above described i.e. the two rotors, the central deflector, the stator and finally the vertical stabilizer (buoy).

The equilibrium equations of the moments, due to the various forces, are better described in [15] together with the machine design procedure. It results that the deflector lift and drag coefficients and the external rotor design are key elements for the whole machine design.

The first aspect has been took in consideration in [15], while the second one is the focus of the present work. In the next section a three-dimensional analysis of the external rotor is carried out.

3. External rotor CFD analysis

The purpose of the CFD analysis is the evaluation of rotor efficiency, power coefficient and flow field characteristics with particular regard to the wake interaction behind the blades. These aspects are, in fact, useful for establishing the effectiveness of the proposed turbine design and for improving any critical points of the design process.

The selected operating condition for the CFD analysis are: a free-stream velocity of 3m/s and an angular speed rotor of 132 rpm, obtained by considering the optimal tip speed ratio λ=2.5 and the external diameter D=1.04 m.

The turbine design is still in a prototype stage; therefore, no experimental data exist for a reliable validation of the current simulations and assessing their accuracy level. However, in this early stage, a preliminary validation is achieved by the comparison of the simulations for a single blade with the theory and the experimental data available in the literature [16-18].

3.1 Computational method, grid and boundary conditions.

The code used for CFD analysis is FLUENT 15 [19]. The code is based on the Reynolds Averaged Navier-Stokes (RANS) approach, in conjunction with the two-equation Realizable k-ε turbulence model.

The rotating machinery is modeled through the use of a moving reference frame and the possibility to enforce the periodic boundary condition allows the reduction of the computational domain, which is built for one sixth of the machine (Fig. 5). The grid is unstructured and is refined on foil and disc surfaces in order to compute the flow field in the boundary layer. This implies a large number of grid points which amount to 1.02 M elements. The grid is cylinder shaped with the cylinder axis coinciding with the machine axis. The boundary conditions can be seen in Figure 5 and are summarized in Table 1; the intake section is one diameter (1D) ahead of the rotor and the outflow section is 1.5 diameters behind the rotor.

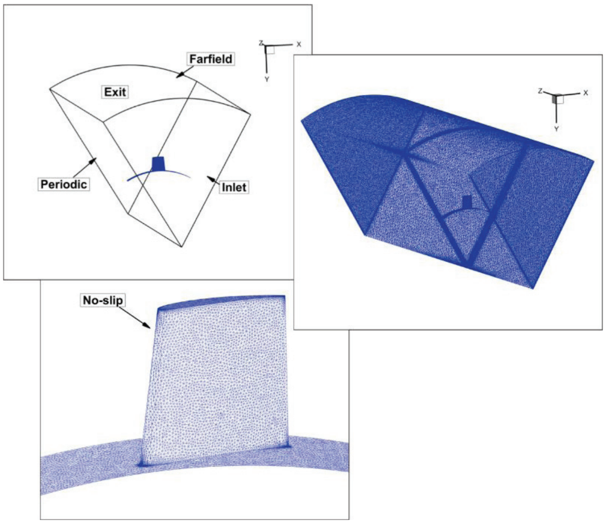

Fig.5 Particulars of the computational domain.

Table 1. Initial and Boundary conditions

Zone	Boundary type	Initial conditions
Inlet	Velocity inlet	$v_0 = 3$ m/s
Exit	Outflow	-
Periodic	Periodic	
Foil	No-slip wall	-
Farfield	Farfield	-

3.2 Results.

Fig. 6 shows the path-lines colored as a function of the flow velocity magnitude. The figure shows that the numerical simulations capture the expected helical wake vortex and the tip vortex on the blade edge; furthermore, no interaction occurs among the blades flow-fields; consequently, in order to validate the simulations, a comparison of the computed lift and drag coefficients with the experimental data available in the literature for an isolated blade is feasible.

The simulation value for lift coefficient is $C_{L,sim}=0.35$; the estimated lift coefficient for the finite length foil is $C_{L,th}= 0.3$. This value is obtained by applying the Pradtl correction [18] to the infinite foil lift coefficient, which, for 4° angle of attack is: $C_{L,inf} = 0.8$. Similar considerations are applied to the drag coefficient: the simulated drag coefficient $C_{D,sim}=0.028$, while the literature value [18], corrected in order to consider the finite length effects, is $C_{D,th}=0.032$. Both for lift and drag coefficient, the agreement is good.

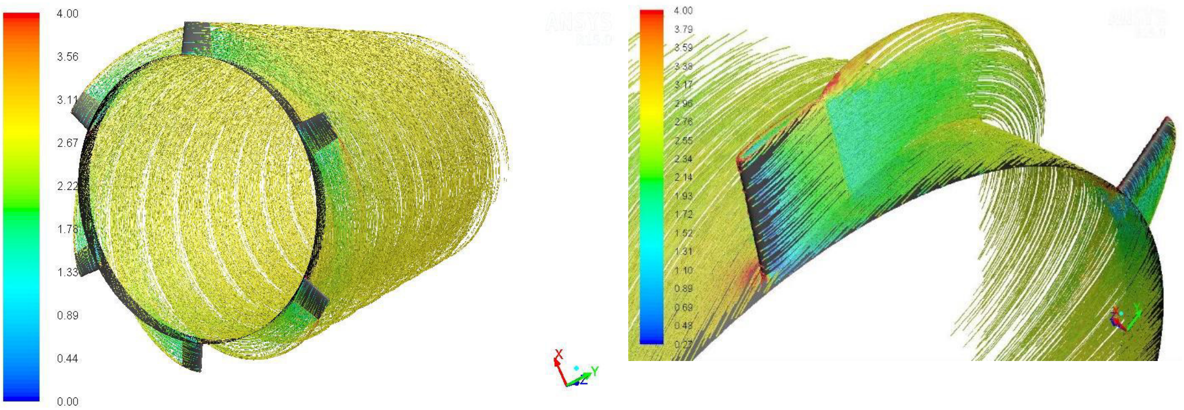

Fig.6 Path lines colored by velocity magnitude: helical vortex wake region (left); tip vortex (right)

Another aspect, well captured by the CFD analysis, is the pressure and speed variation downstream of the rotor. According to Betz theory for ideal wind turbines, in fact, downstream of the rotor, the free stream speed and pressure reduction occur, owing to the power released to the turbine [16-17]. However, the pressure tends to increase and to reach the inlet value; on the contrary, the stream velocity diminishes and reaches the limit value of 1/3 of its undisturbed value. Fig. 7 shows the pressure distribution (left) and the corresponding tangential velocity distribution (right), at several locations of the computational domain, from just behind the disc ($z/D=0.1$) to the domain exit ($z/D=1.5$). It is clearly visible that, after the energy release to the rotor blades, the flow undergoes a strong pressure reduction (Fig 7 top-left), which tends to increase along the axis. The corresponding tangential velocity distribution demonstrates that the pressure increase is due to this velocity component, which reduces in the flow direction – see Fig.7 (right).

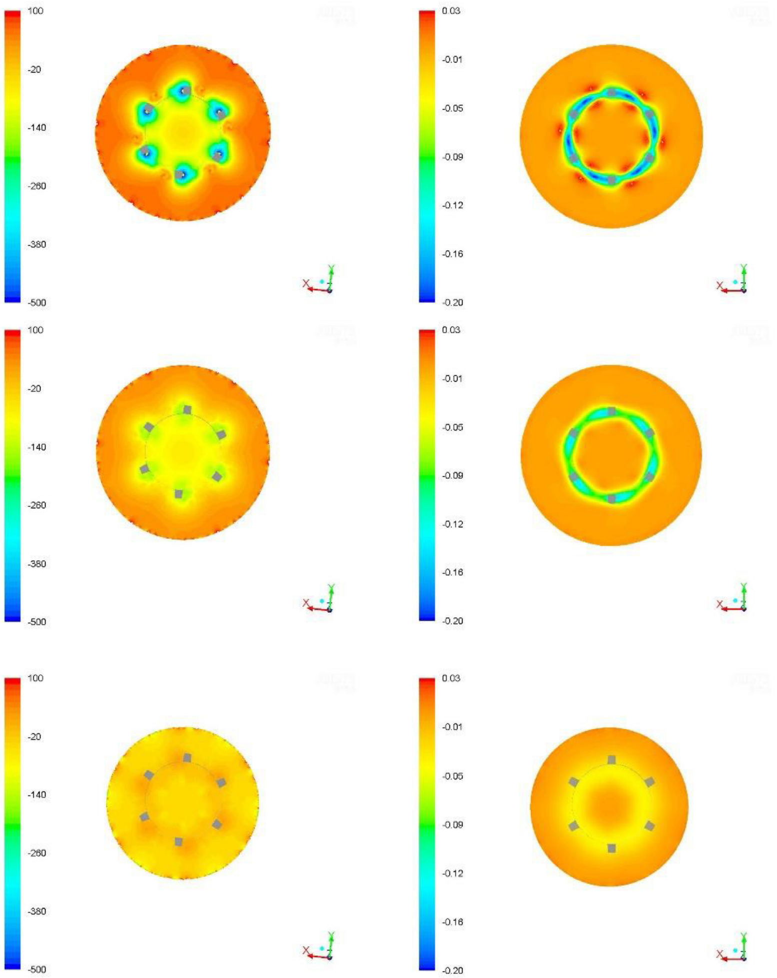

Fig.7 Static pressure distribution (left) and contours of velocity (right) along rotor axis, at sections z/D = 0.1, 0.5,1.5

The numerical results are used to estimate the coefficient of power and the blade efficiency. The power coefficient, defined as the ratio of the power extracted by the turbine to the total power contained in the free-stream, $C_P=P/P_0$, resulting from numerical simulations is $C_P=0.3$ which is significantly less than the Betz limit (59%). Finally, the foil efficiency computed as:

$$E_p = \frac{C_L}{C_D} \qquad (1)$$

amounts to $E_p \approx 10$.

4. Prototype performances

For calculating the optimal machine dimensions the design starts from the parameters λ and z related to the external rotor. As reported in [12], for the optimal configuration it is $\lambda = 2.5$ and $z = 6$. The torques, generated by the rotors, have to be the same since the machine must be in equilibrium, this means that the rotors have the same output power.

Once defined the external rotor power coefficient C_{p1} and the external rotor area A_1, the internal rotor power coefficient C_{p2} and the internal rotor area A_2, are given by imposing the moments equilibrium. The power is then calculated as:

$$P = \eta_e \eta_m \rho \frac{v_0^3}{2} \left(C_{p1} A_1 + C_{p2} A_2 \right) \tag{2}$$

By using eq. 2, the nominal power calculated for a tidal current velocity peak of 3m/s (Strait of Messina – Italy), taking into account an electro-mechanic efficiency of 0.8, will be equal to 2.7 kW.

5. Conclusions

The three dimensional analysis of the flow through the turbine external rotor has been performed using the commercial code Fluent. The main results show the rotor power coefficient lower than the expected coming from zero dimensional analysis.

Assuming an internal rotor power coefficient equal to the internal one the machine sizing has been more accurately done and, due to these results, a maximum output power, at a flow rate of 3 m/s, has been estimated around 2.7 kW.

Once defined machine geometry and calculated the output power, the permanent magnet generator has been designed.

Next development step will be the geometry optimization and the overall performances improvement, based on the first tests on test bench, planned for 2017.

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