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Review of Velocity Profile on the Performance of a Tidal Stream Turbine

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***Abstract*- Work focuses multi-objective optimization of blade sweep for a Wells turbine. The blade-sweep parameters at the mid and the tip sections can act as design variables. The peak-torque coefficient and the corresponding efficiency are the objective functions, which are to be maximized. The numerical analysis has been carried out by solving 3D RANS equations based on k-w SST turbulence model. Nine design points are selected within a design space and the simulations are run. Based on the computational results, surrogate-based weighted average models are constructed and the population based multi-objective evolutionary algorithm gave Pareto optimal solutions.**

Study on use of computational fluid dynamics to investigate the effect of waves and a velocity profile on the performance of a tidal stream turbine (TST) has also been carried out. A full scale TST was transiently modelled operating near its maximum power point, and then subjected to waves both in and out of phase with its period of rotation. A profile was then added to one of the wave models. For this set of conditions it was found that the longer period and in-phase wave had a significant effect on the power range fluctuations, with more modest variations for thrust and the average values, although this is dependent on the turbine tip speed ratio.

Keywords - Wave Energy; OWC Device; Impulse Radial Turbine; Rotor Blade Profile Optimization.

I. INTRODUCTION

Ocean energy is one of the most abundant resources of renewable energy in the world. Its potential in the world is estimated of about 8 000-80 000 TWh/year [1], and on the Moroccan coasts to 744-893 TWh/year [2]. It encloses energy resources such as: wave energy, tidal energy, thermal energy and marine currents energy. Great efforts were made during the last decades, especially in the R&D field, in order to extract this huge energy for covering the continuous growing of the human energy needs. For the wave energy extraction, several energy system converters was introduced, especially the oscillating Water Column (OWC) which is the most used device due to its low cost of installation and the simplicity of its maintenance.

An OWC device (Fig. 1) is composed mainly of three parts: air chamber, air turbine and electrical generator. The first component is used to convert wave energy to pneumatic one; the second is used to convert this pneumatic energy to mechanical energy which is finally converted to electrical energy in the generator. Two alternative types of impulse turbine have been introduced, the axial and the radial one.

II. LITERATURE REVIEW

In [1] author aims to improve the rotor blade performances especially the efficiency of a self-rectifying impulse radial turbine which is in use in OWC devices. Symmetrical blade profile based on use of circular arcs and straight lines has been adopted. A new procedure for optimizing the geometrical blade parameters has been implemented in this work. The Design of Experiments (DOE) method has been adopted with 4 blade geometrical parameters and 2 levels for optimizing the number of numerical tests to determine the optimal profile equilibrating the efficiency between exhalation and inhalation modes.

In [2], a new WEC named wave turbine was proposed. The proposed system consists of a floating body and a submerged body. The floating body is same with that of a conventional buoy, and the submerged body is a power take off similar to a turbine which has flap-type blades in a round-frame rotor. To describe the proposed system, we developed numerical model. The performance of the proposed system was determined by several parameters: wave conditions, floating body geometry, blade shape, rotor hub design, and power storage system including generator and electrical load.

In [3] The influences of blade setting angles on power efficiency and power output were studied in a constant flow direction. The optimal parameters of Wells turbine with different setting angles were obtained in bidirectional flow field. When the turbine's stagger angle was β3 with different airfoils, analysis was performed regarding the fluctuation of power efficiency and power output by the change of the tip speed ratio. It seemed that the turbine with asymmetric profile blades performed better than the turbine with symmetric ones when the tip speed ratio was low

In [4] author describes a new kind of direct-drive wave turbine, which collects wave energy and part of tide through a specially designed turbine device. We select the appropriate wave theory (Elliptic Cosine wave theory), calculate the torque and power, the total energy of wave, energy conversion efficiency through characterization and stress analysis of the turbine blades. We could draw a conclusion that the device is a low number of revolutions of the turbine, which is suitable for the actual ocean wave gathering requirements. The article can provide practical guidance to optimize the design.

In [5] author designed a custom-made flow chamber and performed flow simulations and experiments to evaluate its efficacy. We used a 195-kHz ultrasound transducer operating in continuous-wave mode with acoustic output powers up to 12W. Our acoustic simulations showed that it should be possible to force a 200-μm particle over 2cm in flow, using an acoustic pressure of 12 MPa. Our flow simulations showed, that the fluid flow is not drastically decreased with the flow chamber, which was validated by the experimental measurements. The flow was not reduced when the ultrasound was activated. The acoustic filtering was effective between acoustic powers of 2.6 and 6.4W, where the particle concentration in the clean output was statistically significantly lower than the null experiments.

In [6], author investigate the near-field distribution within and around a wind farm due to a transmitter located outside the farm. To simulate the near field due to the electrically large structure, several simplifications are made. First, the scattered signal from a single turbine is assumed to be dominated by the tower while that from the nacelle and blades are of secondary importance Second, the cone-shaped tower structure is approximated by an infinite circular conducting cylinder, and a 2-D simulation is used to compute the near field. Third, the computation of the near field is accelerated by the use of the complex echo width concept. Lastly, the scattered signals from individual turbines are combined in complex form to obtain the near field around and within a wind farm. The errors introduced by the approximations are quantified against full-wave simulations done using the MLFMM (multilevel fast multipole method) solver in FEKO at 500MHz.

In [7], author introduce a morphing blade for the application of wave and wind energy conversion. The most common and typical wave turbine, the Wells turbine, is symmetrical but rigid, whereas wind turbine blades are asymmetrical with some intended (adaptive) or unintended flexibility. Unlike the Wells turbine which is rigid, the morphing blade is flexible, allowing chord-wise bend from the leading to the trailing edge. The morphing blade discussed here is also symmetrical. It is based on an airfoil that is, in an unloaded state, geometrically similar to the NACA0012 airfoil, the Wells Turbine. The blade's flexibility results in a shape that differs from the NACA0012 airfoil if a load is applied.

III. RADIAL IMPULSE TURBINE BLADE DESIGN

The turbine is composed of a rotating part, the rotor, and a fixed part, the stator.

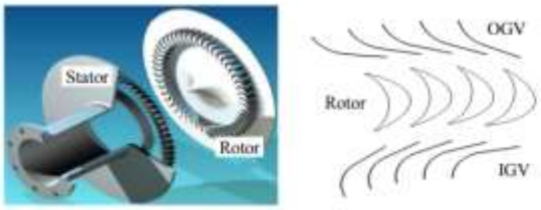

Fig. 1. Rotor and stator of radial impulse turbine

A. Rotor blade profile

A symmetrical rotor blade profile with circular arcs and two straight lines has been adopted. Numerical simulations will be performed for optimizing this rotor blade profile in terms of efficiency improvements [8][9]. The geometrical parameters that define the rotor blade profile with circular arcs in the pressure and suction sides and two straight lines in the leading and trailing edges are shown in Figure 2.

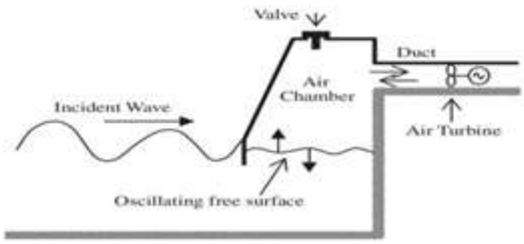

Fig. 2: Oscillating Water Column System

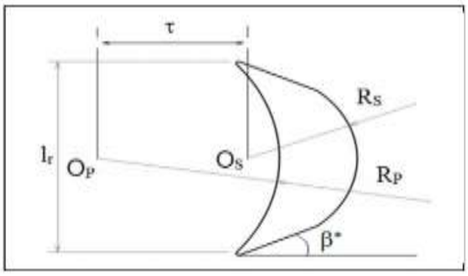

Fig. 3. The rotor blade geometry with circular arcs and straight lines

For this profile type, the radius RP and RS are joined by the Brilings rule yielding a channel of constant width between consecutive blades with the use of the following relationships:

$$R_S = \frac{3}{2} w \text{ and } R_P = \frac{5}{2} w \quad (1)$$

Where w the channel width is (kept constant). From (1), radius R_P and R_S are related by: $R_S = 3/5R_P$

B. Description Of The Wec

The proposed energy harvesting system consists of a floating body and a submerged body, and the two bodies are connected by elastic wire. The floating body functions as a conventional buoy, which contains electrical devices, batteries, navigation sensors, and observation instruments. The submerged body is a power take-off similar to a turbine (Fig. 2), which is called wave turbine. The wave turbine is a self-rectifying wave-induced turbine. The wave turbine has two rotors to countervail rotating moment. Each rotor has flap-type blades hinged on its frame [10]. The angle of attack of the blades change in response to the motion of wave. Thus the flap-type blades generate the lift force in both upward and downward motion of waves, thus the rotor having the flap-type blades is able to rotate continuously [11].

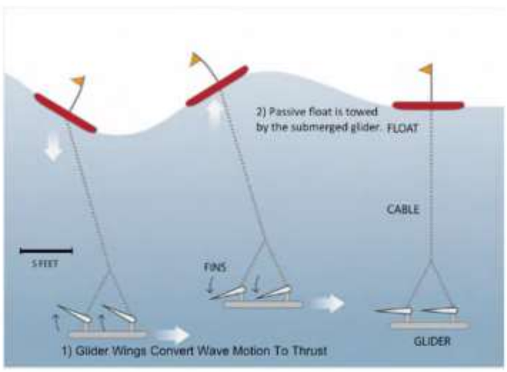

Fig. 4 . Wave turbine prototype 1 (left) and prototype 2 (right).

The mechanisms of the turbine can be explained two stages; vertical stage and horizontal stage. In the vertical stage, as the wave passes over, the floating body moves upward and downward. Assuming the wire is in tension, the submerged body also moves up and down. In the horizontal stage, when the turbine moves vertically, an axial drag force acts on the turbines frame and blades[12].

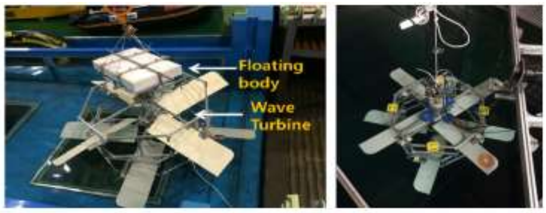

Fig.5. Wave turbine prototype 1 (left) and prototype 2 (right)

The initial prototype (left, Fig. 5) was developed, which has two-layer rotors and four blades on each rotor. Two rotors rotate in opposite directions about same axis, which countervail the rotational moment caused by rotating rotor. At first, the blades were made of aluminum but the aluminum blades were too heavy to turn its angle of attack. So the blades material was changed to acrylonitrile-butadiene-styrene resin (ABS). The reason why we select ABS as blades material is that ABS has similar density with water, which means the ABS blades could be flapped easily with minimum gravitational effect in water [13][14][15]. The maximum flapping angle (angle of attack) was limited to 15 deg.

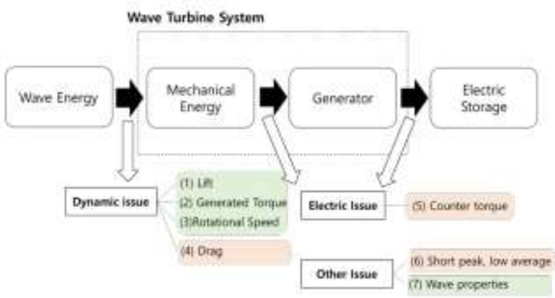

Fig. 6. Energy conversion of Wave turbine and issues surrounding Wave turbine; green background: positive effect to efficiency; red background: negative effect to efficiency

The second prototype (right, Fig. 5) was built with smaller size than the first one, so that quantitative test can be conducted repeatability. In addition, the turbine axis of the second prototype had a room for sensors such as torque meter and encorder. The turbine axis was composed of three-coaxialrotary system [16]. The first coaxial rotary system is the generator shaft. The second coaxial rotary system is turbine axis cylinder itself. The last coaxial rotary system is slip-ring shaft..The advantage by using the design is that there is no gear system with simple structure and minimum torque loss.

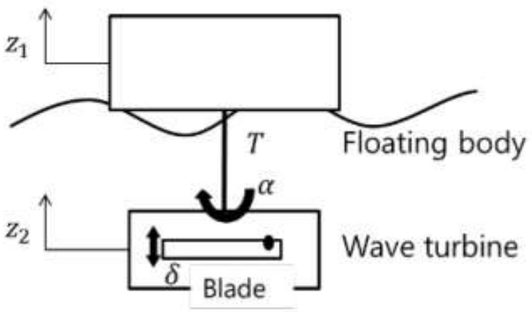

Fig. 7. Schematic image for dynamic modeling of Wave turbine

IV. EXPERIMENTAL DESIGN

DOE method

The DOE method is considered for optimization of this new rotor blade design. In order to validate the effectiveness of this approach and reducing the computation efforts, we have considered performing analyses on 2D turbine geometry. In a first step, the DOE optimization procedure has been applied only to the rotor blade. The others blades for example the inner and the outer fixed guide vanes are kept unchanged [14]. The rotor blade analyses are based on the variation of four input geometrical parameters: the radius (determine inter-centres between two successive blades) and the angle β^* .The radius R_S is calculated from (1). The output result :η is assigned to the turbine efficiency

$$\eta=\frac{T_o.\omega}{\Delta P.q}=C_A / (C_T.\phi) \tag{2}$$

The mathematical model for efficiency dependency on the chosen geometrical parameters is as following:

$$\eta= a_1 + a_2.\ R_P + a_3.\ l_r + a_4.\beta^* + a_5.\ \tau \tag{3}$$

In which: ai , i=1…5 are variables to be determined for each design in both modes of turbine operation (Exhalation and Inhalation). Equation (3) will be used for the optimized geometrical parameters.

The numerical tests have been carried out with ANSYS FLUENT 15.0 in order to extract the rotor torque for different (Exhalation: 0.5, 1, 1.5, 2 and 2.5 /ϕflow coefficient Inhalation: -0.5, -1, -1.5, -2 and -2.5). The flow turbulence is modelled by the standard k-ε model. The coupled conservation equations of mass, momentum and energy are solved using a segregated solver. The algorithm of SIMPLEC is adopted to perform the pressure-velocity coupling. Since the turbine is composed of rotating and fixed components, the sliding mesh technique has been used to manage the relative movement between the fixing and the moving part of the turbine. The boundary conditions adopted is a uniform total pressure at the inlet and a uniform static pressure at the flow outlet. The condition of non-slip is adopted for all the walls [17].

V. THEORETICAL CALCULATION AND ANALYSIS

A. Choice of Wave Theory

Currently, there are three common wave theories: Linear wave theory , Stokes high-order wave theory, Elliptic cosine wave theory. Each wave theory are obtained by simplifying assumptions, based on different assumptions and simplifications, the theoretical results are different, also have their own scope.[1]

(1) $T\sqrt{g/d}$ <6.0 (equal d/L>0.2), H/d≤0.2, use Linear wave theory;

(2) $T\sqrt{g/d}$ ≤10.0(equald/L≥0.1), use Stokes high-order wave theory;

(3) $T\sqrt{g/d}$ >10.0(equal d/L<0.1), use Elliptic cosine wave theory.

T is the wave period, d is the depth, L is the wave length, H is the wave height.[2]

T is the wave period, d is the depth, L is the wave length, H is the wave height.[2] In this article,the water depth d=1.0m'T $\sqrt{g/d}$ =3.6 we use Elliptic cosine wave theory.

Tidal wave is the finite amplitude wave and long period wave under conditions of shallow depth . It is called elliptic cosine wave because the wave surface height is represented as Jacobian elliptic cosine function. There are three tidal wave [18] numerical methods, namely arithmetic - geometric mean method, the small parameter method and empirical relationship parameter method. Here we adopt the arithmetic - geometric mean method. [3] The formula of the elliptic cosine wave of wavefront,wavelength,velocity is:

$$\eta = Hcn^2[2K(\frac{x}{L}-\frac{t}{T}),m]$$

$$L=\sqrt{\frac{16d^3}{3H}}mK$$

$$C=\sqrt{gd\{1+\frac{H}{d}[-1+\frac{1}{m^2}(2-3\frac{E}{K})]\}}$$

Where L,C,H represent wavelength,velocity ,wave high of the elliptic cosine wave;d is depth; t, x represent the time and the position coordinates of calculated point; m is the modulus of elliptic integrals; cn is elliptical cosine symbol; g is acceleration of gravity; K, E, represent the first and second categories complete elliptic integrals:

$$K=\int_0^{\frac{\pi}{2}}\frac{d\varphi}{\sqrt{1-m^2\sin^2\varphi}}$$

$$E=\int_0^{\frac{\pi}{2}}\sqrt{1-m^2\sin^2\varphi}\,d\varphi$$

After multiple iterations, the wavefront equation, wavelengt h velocity, and other related amount are obtained, creating basis for subsequent mechanical analysis and wave energy calculation [19][20].

B. Stress Analysis of a Single Blade

First, analyze the single blade. when the blade is located on T ,the formula of the lift force, the drag force on the blade, the center o of the torque M_0 is:

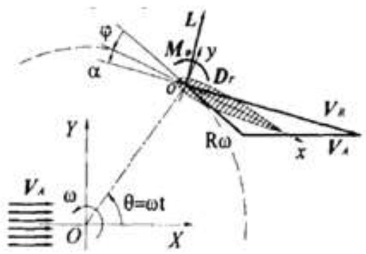

Fig. 8 : Stress Analysis of Single Blade

$$L=\frac{1}{2}\rho C V_R{}^2 C_L$$

$$D_r=\frac{1}{2}\rho C V_R{}^2 C_D$$

$$M_0=\frac{1}{2}\rho C^2 V_R{}^2 C_{M_0}$$

Where, U is relative velocity, C is chord,C_L is lift coefficient C_R is drag coefficient, V_R is combined velocity ˈ M_0 C is torque coefficient.[4] Combined velocity V_R ˈstream velocity V_A (equal wave velocity C)ˈrotation speed Z ,the relationship among the three is:

$$\vec{V}_R=\vec{\omega}\times R+\vec{V}_A$$

$$V_x=V_R\cos\alpha=V_A\sin(\theta+\varphi)+R\omega\cos\varphi$$

$$V_y=V_R\sin\alpha=V_A\cos(\theta+\varphi)-R\omega\sin\varphi$$

Where, V_x, V_y is the decomposition rate of combined velocity(V_R) along x-axis and y-axis under local coordinate system oxyz; geometric angle of attack α is the angle between relative velocity V_R and the blade chord line; vane angle Φ is the blade chord line deviating from the circle tangent track hinge angle, [18] for stationary turbine blade angle, it is usually Φ ,that the blade chord line is always tangent to the circle. Relative velocity V_R and blade angle of attack D can be expressed as:

$$V_R=\sqrt{V_A{}^2+(R\omega)^2+2R\omega\cdot V_A\sin\theta}$$

$$\tan\alpha=\frac{V_A\cos(\theta+\varphi)-R\omega\sin\varphi}{V_A\sin(\theta+\varphi)+R\omega\sin\varphi}$$

C. Stress Analysis of Blades and Device

For turbine stationary angle (Φ=0)ˈthrough the blade lift and drag along the device locus circle at tangential and radial decompositionˈit can be obtained the Tangential Force F_t Radial force F_n of the rotor from a single blade.

$$F'=(F_t,F_n)=(D_r,L)\begin{pmatrix}-\cos(\alpha+\varphi) & \sin(\alpha+\varphi)\\ \sin(\alpha+\varphi) & \cos(\alpha+\varphi)\end{pmatrix}$$

Obviously, for the angle fixed turbine, the rotor tangential force epuals the blade chord force; the rotor radial force equals the blade normal force. [5] Single blade rotor thrust and lateral forces can be expressed as follows:

$$t=(t_x,t_y)=(D_r,L)\begin{pmatrix}\sin(\alpha+\theta+\varphi) & -\cos(\alpha+\theta+\varphi)\\ \cos(\alpha+\theta+\varphi) & \sin(\alpha+\theta+\varphi)\end{pmatrix}$$

Therefore, the force on a single blade turbine rotational torque center:

$$q=F_tR+M_0=R\cdot[L\sin(\alpha+\varphi)-D_r\cos(\alpha+\varphi)]+M_0$$

The above are all about the single blade and the force effect on the rotor, but the combined force of the rotor can be obtained by adding up all the single forces.In the device rotating process, the blades do periodic and unsteady movement, movement and force of expression above are determined by the kinds of time (azimuth Φ) function. The average thrust force T_x ,the average lateral force T_y , the average torque Q and the average power P of the rotor is the average force of the device in a period of time [19]. They depend on the form (structure, size, blades)of the device, the load and the stream (reflecting by working ratio) and other factors, regardless of the azimuth angle, and can be expressed as follows:

$$T_x = \frac{Z}{2\pi}\int_{\frac{\pi}{2}}^{\frac{3\pi}{2}} t_x(\theta)d\theta ,\ T_y = \frac{Z}{2\pi}\int_{\frac{\pi}{2}}^{\frac{3\pi}{2}} t_y(\theta)d\theta$$

$$Q = \frac{Z}{2\pi}\int_{\frac{\pi}{2}}^{\frac{3\pi}{2}} q(\theta)d\theta ,\ P = \frac{Z}{2\pi}\int_{\frac{\pi}{2}}^{\frac{3\pi}{2}} q(\theta)\omega d\theta$$

The average particle fluid wave energy on can be represented:

$E = E_k + E_P$

Where, E_k= Wave kinetic energy

E_P=Wave potential

VI. CONCLUSION

Tidal energy may be harnessed by tidal power stations, wave energy converters, osmotic power plants, ocean thermal energy converters (OTEC) and ocean thermo-electric energy converters (OTEG) devices. Tidal power stations produce in the range of tens to hundreds of MW like hydel power stations, wave energy converters (WECs) from a few kW to MW. Tidal barrages, WECs, OTECSs and osmotic plants are used commercially. Of course, tidal energy is clean and renewable in nature, yet has minor environmental reservations. In this paper, a study of WEC named wave turbine is discussed. The performance of the WEC system may be determined by several parameters: wave conditions, floating body geometry, blade shape, rotor hub design, and power storage system including generator and electrical load. In this study, we found optimal design of blade and rotor hub size from quantitative simulation by using the numerical model. In future work, a prototype would be constructed to conduct experimental analysis.

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