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CFD Hydrodynamics Forces Determination for a Darrieus Turbine Rotating Blades Using K-ε Turbulence Model

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Abstract: Determination of hydrodynamic forces acting on the blades of Darrieus turbine used to harness water energy from dams, rivers and ocean is very important to evaluate this turbine performance. Therefore, this paper presents the numerical results of CFD investigation using K-ε closure turbulence model. This simulation has been performed for a hydro Darrieus turbine that we have previously tested experimentally; this turbine has a diameter of 21.5 cm and it is composed of three NACA0020 blades, with a height of 23 cm and a cord of 7 cm, that are fixed with a separation angle of 120 °. The present simulation has been carried out for a water flow velocity of 0.67 m/s and the Darrieus turbine rotating velocity of 125 rpm. These values correspond to a specific velocity λ equal to 2, a flow Reynolds number Rev equal to 4.57 104, a rotational Reynolds number Reu equal to 1.97 105 and a relative Reynolds number Rew varying between 4.72 104 and 1.39 105. The graphical presentations of the simulation numerical results have shown practically identical curves, respectively for the hydrodynamic lift and drag forces variations versus the rotational angle (position angle of each blade) with a phase angle of 120° between the first blade and the second one and of 240° between the first blade and the third one. The hydrodynamic blade element lift force varies between 0.0454 and 0.641 N while the drag force varies between - 0.0968 and 0.342 N. The global turbine hydrodynamic lift and drag forces (for the three blades elements together) varies respectively between 0.5928 and 0.9251 N and between 0.0335 and 0.2497 N. The maximal values show that the lift is about twice the drag for each blade and about four times for this turbine. The turbine average lift and drag forces over three rotations are respectively 32.38 N and 6.61 N.

Keywords: Water energy, Darrieus turbine, Hydrodynamic forces, Simulation, Turbulence model

Introduction

Renewable energies, as an alternative to non-renewable fossil energies, are getting increasing attention, especially in remote areas. The main reasons are the continuous increase of global warming effects and fossil

energies decreasing availability. To harness water energy of hydraulic reservoirs with small head, rivers and sea currents the use of Darrieus turbine is getting growing interest and the prediction of the hydrodynamics forces acting on this turbine is becoming necessary and important.

Benzerdjeb, Abed, Hamidou, Bordjane and Gorlov (2017) conducted an experimental study for a vertical axis water Darrieus turbine. The experimental tests were carried out for a Darrieus turbine model with its three blades fixed with geometric angle of incidence equal to 0°. The experimental results have shown, for a relative increase of the water flow velocity of 100%, a 604% relative increase for the generated mechanical power by this turbine. Another experimental investigation on the effect a Darrieus turbine blades orientation angle, presented by Benzerdjeb, Abed, Achache, Hamidou and Gorlov (2018), have shown the optimal performance has been obtained when this angle is set to 1.75°.

To show the importance of water energy, Shahinur, Sabuj Shah, Nazmul and Ashraful (2013) presented an analysis of the possibility of using small-scale hydro power plant in Surma and Gumoti (Bangladesh) and deducted that these two rivers can produce respectively 14.804 MWhr and 18.834 MWhr per year. The experimental study presented by Rus T., Rus L.F., Abrudan, Domnita and Mare (2016) shows that, for the same velocity, vertical axis wind turbines rotate at lower RPM than water turbines. Maître, Amet and Peltone (2013) presented a wall grid analysis and comparison with experiments. Their study showed that a too coarse wall grid leads to early and overestimated stalls and have negligible contributions on the power. Ploesteanu, Tarziu and Maître (2003) conducted a study on the flow modeling for a Darrieus turbine at moderate Reynolds number and found that the determined effort coefficients results show significant deviations from the experimental ones.

The experimental study on a modified hydrokinetic four bladed Savonius turbine, conducted by Thyagaraj, Rahamathullah and Suresh Prabu (2016), has improved the power coefficient from 0.16 to 0.19. Sanusi, Soeparman, Wahyudi and Yuliati (2016) carried out and experimental study of a wind Savonius turbine with combined blades; their results show an increase of the maximum power coefficient by up to 11 % with respect to the conventional blades at the tip speed ratio (TSR) of 0.79. An experimental study, was carried out by Kaprawi, Santoso and Sipahutar (2015), for a combined Darrieus and Savonius water turbine placed in a river, during which, they found that the maximum power coefficient of 0.19 and torque coefficient of 0.107 were obtained when the attaching angle on the returning side of Savonius bucket β is set to 30°.

Work Objective

The objective of the present numerical work is to conduct a 2D CFD simulation to evaluate the hydrodynamic lift and drag forces acting on the three rotating NACA0020 blades elements of a water Darrieus turbine versus the rotational angle (position or azimuthal angle of each blade). The academic ANSYS CFX R18.1 and the K-ε closure turbulence model with sliding mesh technique are used. The simulation will be performed for a Darrieus turbine model that we have previously tested experimentally in water flowing at 0.67 m/s and for maximal mechanical power rotating velocity of 125 rpm (Benzerdjeb et al., 2017). The corresponding specific velocity λ is equal to 2, free flow Reynolds number Rev is equal to 4.57×10^4 and rotational Reynolds number Reu is equal to 1.97×10^5. This model has a diameter of 21.5 cm and a height of 23 cm and its blades cord is 7 cm.
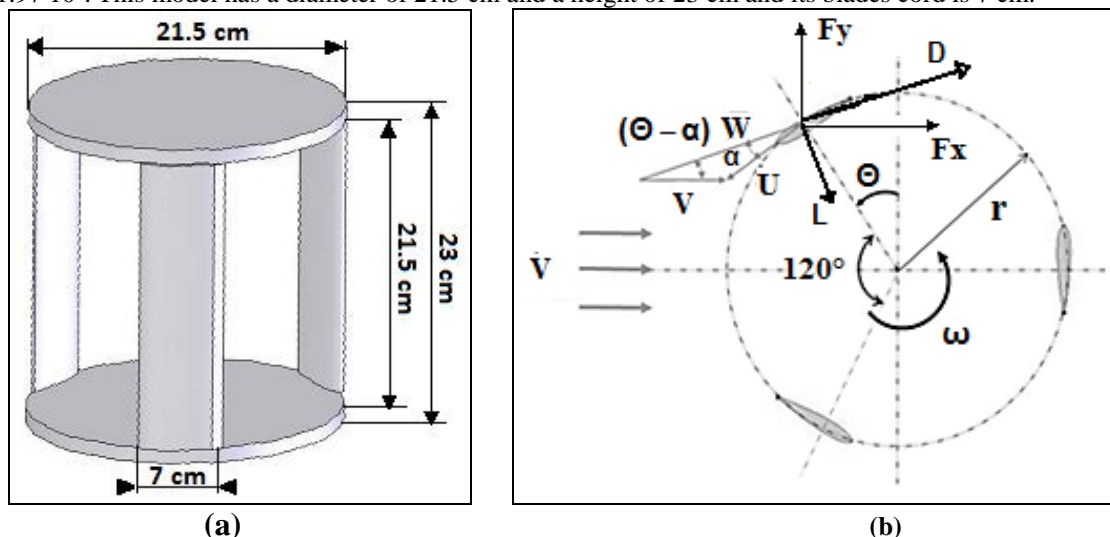


(a)   **(b)**

Figure 1. (a) Darrieus turbine model (b) section with velocities and forces
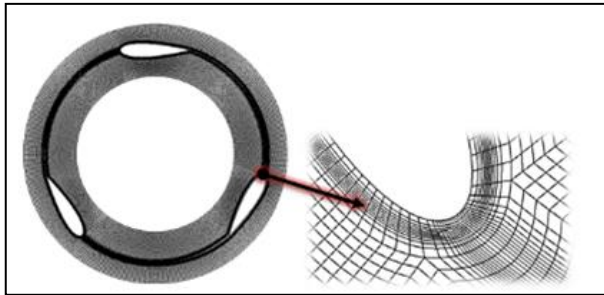
Numerical Presentation

The numerical simulation, of the water Darrieus turbine (figure 1), uses the academic ANSYS CFX R18.1, with a scheme of high resolution to estimate the convective terms of the transport equations. The numerical domain is divided into three part (figure 2): two fixed domains (D1 and D3) and a rotating one (D2) that models the turbine rotational zone. A hexahedral mesh is generated (Table 1) and the sliding mesh technique is used (ANSYS® Academic Research Mechanical, Release 18.1, 2017).
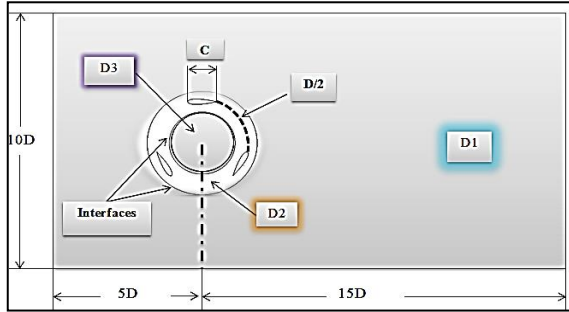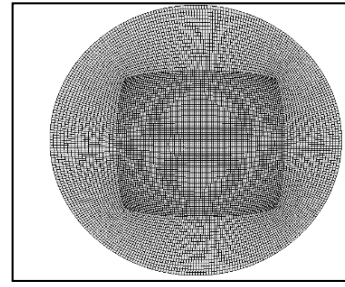

(a) Numerical domains and meshes
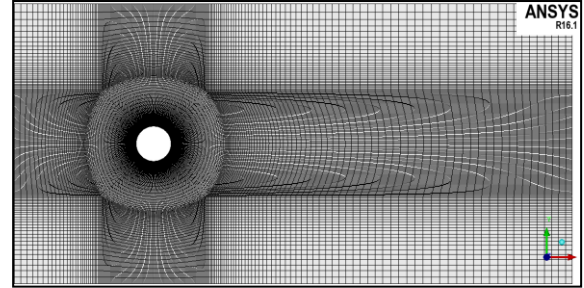
(b) Numerical meshes

(c) Domain D2 mesh with zoom

(d) Domain D3 mesh

Figure 2. Numerical domains and meshes

Table 1. Domains mesh nodes and elements

Domain	D3	D2	D3
Number of elements	31820	22321	13440
Number of nodes	64744	45770	27218

Formulation

Figure 1 (b) represents an axial section of the Darrieus turbine with the free flow velocity V, the rotational velocity U, the relative velocity W, the numerical forces Fx and Fy and the hydrodynamics lift and drag forces L and D acting on the turbine blades.

The relative velocity of the fluid W and the angle of attack α cannot be measured, therefore they will be expressed in terms of the known fluid velocity, Darrieus turbine rotational speed and the position angle of the blade θ which are shown in figure 1 (Arief., Musriyadi, & Aldara, 2018). From this figure, we can see that,

$$Usin\alpha = Vsin(\theta - \alpha)$$

(1)

$$Ucos\alpha = W - Vcos(\theta - \alpha)$$

(2)

After developing Sin (θ-α) and Cos (θ-α) equations 1 and 2 give,

$$\alpha = \tan^{-1}\left[\frac{V\sin\theta}{U + V\cos\theta}\right] \tag{3}$$

and

$$W = \sqrt{U^2 + V^2 + 2UV\cos\theta} \tag{4}$$

The free flow, the relative flow and the rotational Reynolds numbers, respectively Re_V, Re_W and Re_U, based on the blade chord C, are given (Maître et al., 2013) and (Paillard, Hauville and Astolfi, 2013) by,

$$Re_V = \frac{CV}{\nu} \tag{5}$$

$$Re_W = \frac{CW}{\nu} \tag{6}$$

$$Re_U = \frac{CU}{\nu} \tag{7}$$

where ν is the water kinematic viscosity.

The hydrodynamic lift and drag forces can be expressed in term of the simulation numerical forces as,

$$L = F_x \sin(\theta - \alpha) - F_y \cos(\theta - \alpha) \tag{8}$$

$$D = -F_x \cos(\theta - \alpha) - F_y \sin(\theta - \alpha) \tag{9}$$

Results and Discussion

As shown on figure 3, when the rotating turbine blade is in the first half of rotation (θ from 0° to 180°) the relative Reynolds number decreases from $1.39\ 10^5$ to $4.72\ 10^4$ then it increases again to $1.39\ 10^5$ when the blade is in the second half (θ from 180° to 360°). The free flow and rotational Reynolds numbers remain equal respectively to $4.57\ 10^4$ and $9.28\ 10^4$. We can see also, that the blade angle of attack increases from 0° to 29.5° when its position (azimuthal) angle changes from 0° to 120° then it deceases to 0° at $\theta =$180°. In the second half of the rotation the angle of attack becomes negative with a minimum of -29.40° at $\theta =$240°.
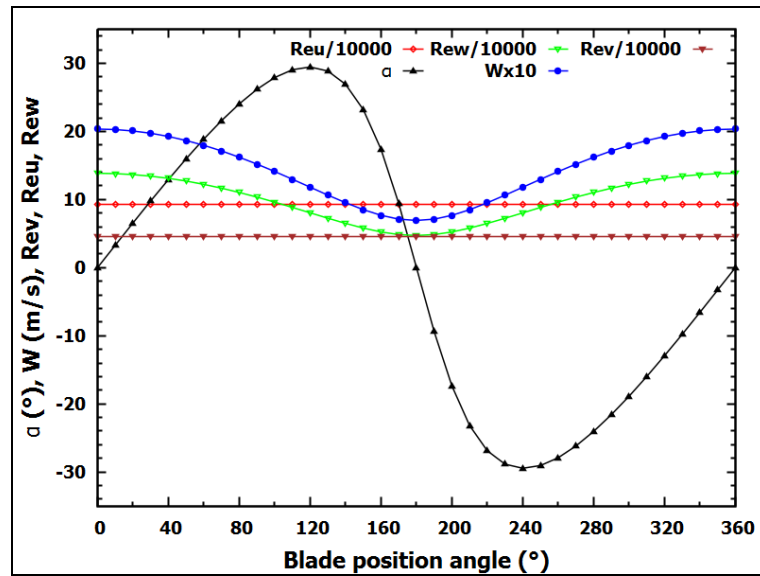

Figure 3. Attack angle, relative velocity and reynolds number

First, we should remind that the three blades are fixed apart with a phase angle of 120°. However, in figure 4 to 7 this phase angle is not considered mainly to get the right global force acting on the turbine, which is given by the summation of the forces acting on the three blades.

On figure 4, we can see that the curves of the numerical horizontal forces acting on the full blades are similar when considering the shift angle of 120° between the first and second blade and of 240° between the first and third blade. There is insignificant differences between these three forces for each blade position. .Indeed, the maximal values are 29.30 N, 29.37 N and 29.24 N respectively for blades 1, 2 and 3 (at $\theta \approx 80°$), while the corresponding minimal values are respectively -7.49 N, -7.53 N and -7.43 N. The total force varies between 3.89 and 23.07 N. The global turbine element horizontal forces (for the three blades elements together) are between 0.0904 and 0.5366 N (not presnetd on this figure). The average horizontal force for three revolutions is equal 13.7644 N.
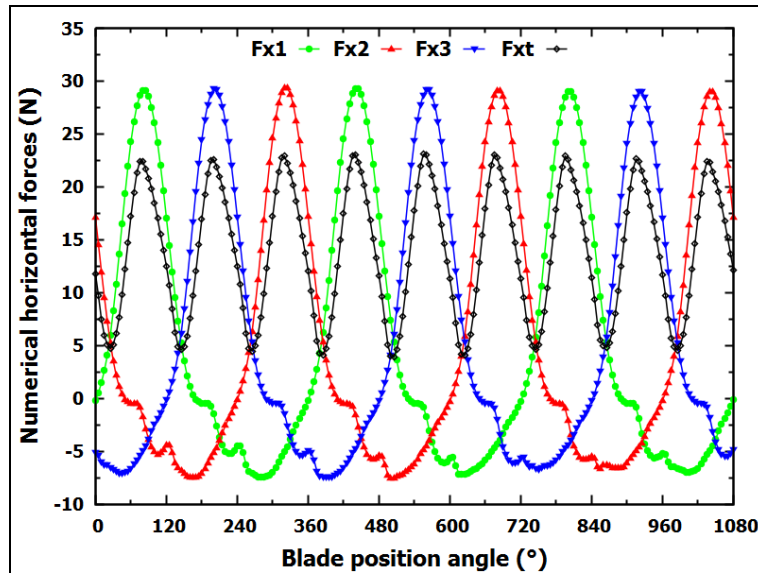

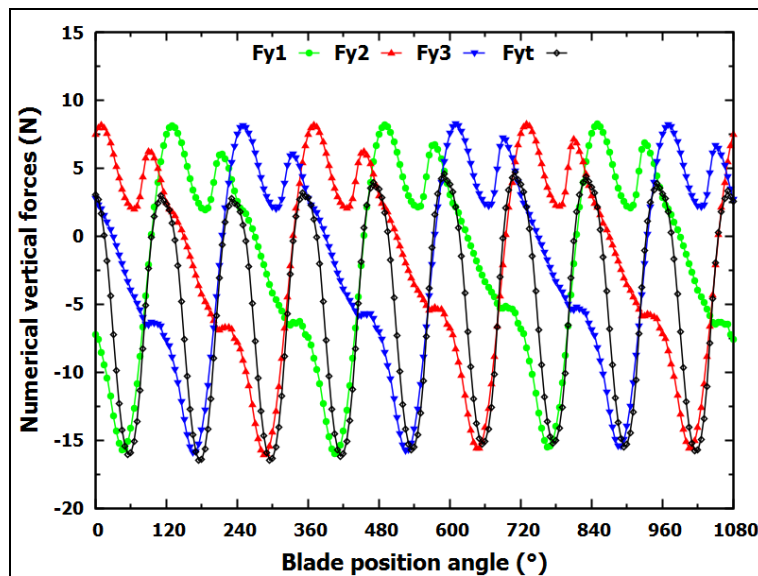Figure 4. Horizontal forces for each blade and the turbine

Figure 5. Vertical forces for each blade and the turbine

Figure 5 shows also similarity between the curves for the horizontal forces acting on the blades with a shift angle of 120° and 240°, respectively between the first and second blade and between the first and third blade. The maximal values are 8.22 N, 8.25 N and 8.27 N respectively for blades 1, 2 and 3 (at $\theta \approx 80°$), while the minimal values are respectively -16.00 N, -16.08 N and -15.91 N. The total force acting on the turbine is mostly negative and varies between 4.68 and -16.49 N. The global turbine element vertical forces (for the three blades elements together) are between -0.3836 and 0.1089 N (not presnetd). This maximal vertical force is 20% of the maximal

horizontal one. The average vertical force over three rotations is -5.3339 N, which is about 39% the horizontal average force.

As shown on figure 6, the curves of the hydrodynamic lift forces acting on the turbine blades have identical behavior and the differences are negligible. In fact, the lift force for the three blades L_1, L_2 and L_3 varies respectively between 27.64 and 2.01 N, 27.63 and 2.01 N and 27.5 and 2.04 N. Hence, the force acting on the turbine changes between 25.49 and 39.78 N. The global turbine element lift forces (for the three blades elements together) vary from 0.5978 to 0.9251 N (not presnetd). The turbine average lift force over three rotations is 32.38 N.
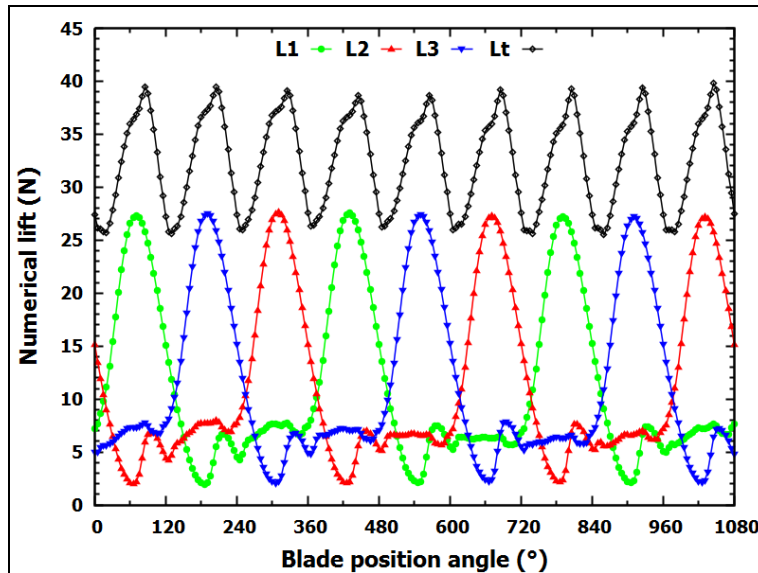

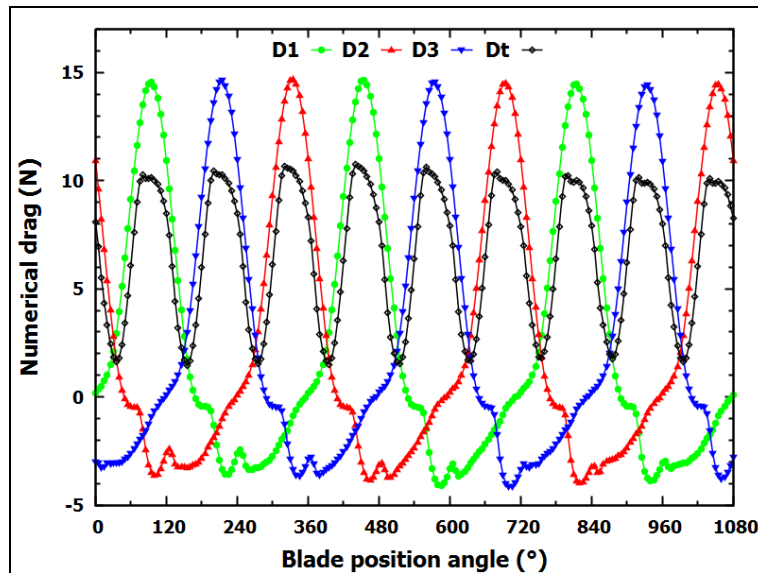Figure 6. Lift forces for each blade and the turbine

Figure 7. Drag forces for each blade and the turbine

We can see from figure 7 that the variations of the hydrodynamic drag forces acting on the turbine blades are the same with very small differences. The drag force for the three blades D_1, D_2 and D_3 changes respectively from -4.11 to 14.64 N, -3.98 to 14.69 N and -4.16 to 14.62 N. This gives a force acting on the turbine between 1.44 and 10.74 N.The corr'esponding global drag forces for the blades elements change between 0.0335 N and 0.2497 N (not presnetd on the figure). The average of the turbine drag force over three rotations is 6.61 N. This maximal drag force is equal to 20% of the maximal lift force.

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Conclusion

To evaluate the hydrodynamic lift and drag forces acting on a water Darrieus turbine three rotating NACA0020 blades elements versus their azimuthal angle, a 2D CFD simulation, using the academic ANSYS CFX R18.1 and the K-ε closure turbulence model along with sliding mesh technique, has been conducted. This simulation has been performed for a 21.5 cm wide and 23 cm high turbine that we have experimentaly tested in a previous work in a 0.67 m/s water flow (free flow Reynolds number Rev equal to $4.57\ 10^4$) and at rotational velocity of 125 rpm (rotational Reynolds number of $1.97\ 10^5$).

The analysis of the simulation numerical results has given the following findings:

◆ there is a very close agreement between each type of forces acting on all three blades (horizontal, vertical, lift and drag forces);
◆ the global horizontal forces for the turbine three blades elements together vary from 0.0904 to 0.5366 N;
◆ the average for the global horizontal force for three revolutions is 13.7644 N;
◆ the global vertical forces for the turbine three blades elements are between -0.3836 and 0.1089 N;
◆ the maximal vertical force is 20% of the maximal horizontal one;
◆ the average vertical force over three rotations is -5.3339 N, which is about 39% the horizontal average force;
◆ the global turbine elements lift forces vary from 0.5978 to 0.9251 N;
◆ the turbine average lift force over three rotations is 32.38 N;
◆ the average of the turbine drag force over three rotations is 6.61 N;
◆ the maximal drag force is 20% of the maximal lift force.

Acknowledgements

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