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Numerical simulations of biofouling effects on the tidal turbine hydrodynamic

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Abstract

Biofouling by benthic organisms (barnacles, mussels) must be considered for tidal turbine operation and maintenance because it modifies hydrodynamics (drag and resistance) and could be detrimental to the turbine performance. We investigate vortex modifications downstream of a tidal turbine due to biofouling using numerical modeling. Firstly, 2D flow downstream of a clean Darrieus vertical axis tidal turbine is simulated using a dynamic mesh for different tip speed ratio. Results agree former studies. Simulations are very sensitive to turbulence modelling. To ensure an acceptable computing time, only Large Eddy Simulation (LES) and Reynolds Averaged Navier-Stokes (RANS) models are used. Secondly, an airfoil with barnacles is modelled in two dimensions for various fouling heights and spacings. Then barnacles and mussels with various characteristics are fixed on blades. Vorticity fields are strongly changed by organism shapes. Mussels size has little impact on vorticity patterns. A few mussels could have stronger impact than a fully colonization. A 3D simulation is performed with a shape of barnacles from new in-situ measurements. Finally a colonized tidal turbine is simulated. Vortices around the tidal turbine are clearly modified.

Index Terms

Tidal converters, Biofouling, Hydrodynamic modeling, Computational Fluid Dynamic, Turbulence

I. INTRODUCTION

Biological organisms, like algae, barnacles, mussels or bryozoans, colonize rapidly an immersed surface (e.g. buoy, ship bottom and propeller) and could form a thickness until several centimeters on it. This biofouling have to be considered for tidal turbine operation and maintenance because it modifies hydrodynamics (e.g. [1], [2]) by increasing drag and hence resistance and could be detrimental to the performance of turbine. This problem is well documented in the field of maritime transport, with, in particular, biological fouling of ship propellers (e.g. [3], [4]). Anti-fouling coatings have been developed over the last 30 years to reduce organism fixation (e.g. [5], [6]), but are not harmless to surrounding

aquatic ecosystems. Concerning renewable energy, research has been carried out on the aerodynamic impact of dirt on wind turbine blades. These dirt, modelled as shape roughness, modify lift and drag forces, as biological organisms could do. Many authors reported that presence of dirt decreases lift and increases drag (e.g. [7]). These changes in lift and drag are rapid until a threshold value (e.g. 0.3mm for a pale with a chord of 1 m) beyond which changes evolve more slowly [8]. [9] showed experimentally that the power produced by the wind turbine decreases with increasing fouling of the blades. [7] explained that roughness at the leading edge also had a significant influence on lift (i.e. a decrease) and drag (i.e. an increase). In the case of tidal turbines, there have been few studies which investigate the hydrodynamic impact of biofouling [10], as this is not a priority for industrials. [1] and [2] assessed, experimentally and numerically respectively, impact of barnacle colonization on a blade on lift to drag ratio. [11] showed that tidal turbine performance was adversely affected in the case of blades roughened with a thin layer of randomly applied contact cement to model increased blade roughness or growth by hard deposits such as barnacles or encrusting bryozoans. Links between physical and biological processes are not well known in areas with very strong currents. However tidal turbines can increase physical complexity and slows down currents (e.g. [12], [13]). These devices may act as potential localised artificial reef structures [14].

Benthic sampling per dredge recorded in 2015-2016 has permitted to describe the actual fauna found in the Alderney Race (Raz Blanchard in french) [15], where tidal turbines have planned to be installed. Animal communities in this dynamic zone are closely related to the mobile coastal circalittoral gravel and pebbles with the calcareous tubiculous polychaete *Spirobranchus triqueter*, barnacles and encrusted Bryozoans; this habitat may occasionally contain large numbers of juveniles *M. modiolus*. The horse mussel *M. modiolus* which can reach a maximum length of 22 cm but currently length of 10 cm was reported in some parts of the Alderney Race during the investigations carried out by [16] in the 1970s, forming

mussel beds in an area which corresponds to the southern limit in this part of the English Channel, but this mussel was not recorded in 2015-2016. Conversely, in the samples large populations of the green crenella *Musculus discors* (a small mussel with a maximum length of 12 mm) are collected within large barnacles *Balanus crenatus* (maximum size 25 mm).

Our work focuses on modifications of vortices downstream a tidal turbine due to biofouling using a Computational Fluid Dynamics (CFD) software. Fixed biological organisms are

solved explicitly by the model and are considered by modifying the roughness of blade profile. This work is composed by two steps. Firstly, simulated flow around a clean tidal turbine is validated by comparison with measurements made by [17] and with numerical simulation made by [18]. Secondly, sessile benthic species (barnacles and mussels) are fixed on a single blade and on blades of a tidal turbine and the modifications due to bio-fouling are assessed by comparison between clean and colonized structure.

II. MATERIALS AND METHODS

This study is done using the open source software OpenFoam 2.3.0 [19]. The governing equations are :

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\frac{1}{\rho} \nabla p + \frac{1}{\rho} \mathbf{f} + \nu \Delta \mathbf{u} \quad (1)$$

$$\nabla \cdot \mathbf{u} = 0 \quad (2)$$

where $\mathbf{u}$ is the fluid velocity vector, t is the time, ρ is the fluid density, p is the pressure, $\mathbf{f}$ is the volumetric forces and ν is the fluid viscosity.

Turbulence is solved using two types of turbulence models: RANS (Reynolds Averaged Navier-Stokes) with the standard $k-\epsilon$ and the $k-\omega$ SST (Shear Stress Transport) schemes, and the LES (Large Eddy Simulation) modelling of [20] are

used. RANS models are based on a statistical approach. $k-\epsilon$ scheme is a two transport equations model and solves the turbulent kinetic energy k and dissipation ϵ [21], [22]. $k-\omega$ SST is a variant of the $k-\omega$ scheme which computes the turbulent kinetic energy and frequency ω . This version of $k-\omega$ SST [23] combines the original Wilcox [24] $k-\omega$ model for use near walls and the standard $k-\epsilon$ model away from walls using a blending function to avoid sensitivity problem at these locations. The eddy viscosity formulation is modified to account for the transport effects of the principle turbulent shear stress. LES model directly solves scales from the domain down to the a filter size while the effects of sub-filter scales are parameterized. The Smagorinsky subgrid-scale model used in this study is described in [20]. LES is more computational expensive than RANS.

TABLE I
DESCRIPTION OF SIMULATIONS IN CASE OF ONLY ONE BLADE.

N°	Fluid	Turbulence model	Input current	Colonization	3D/2D	Figures
1	air	$k-\epsilon$	34 m/s	Barnacles with 3 heights and 3 densities	2D	5
2	air	$k-\epsilon$	2.3 m/s	Barnacles: Medium height and medium density	2D	6a
3	water	$k-\epsilon$	2.3 m/s	Barnacles: Medium height and medium density	2D	6b
4	water	$k-\epsilon$	2.3 m/s	No colonization (clean)	2D	7a
5	water	$k-\epsilon$	2.3 m/s	Fully coverage with medium barnacles	2D	7b
6	water	$k-\epsilon$	2.3 m/s	Fully coverage with mussels of 0.7 cm	2D	7c
7	water	$k-\epsilon$	2.3 m/s	Fully coverage with mussels of 1 cm	2D	7d
8	water	$k-\epsilon$	2.3 m/s	Fully coverage with medium barnacles and isolated mussels of 1 cm	2D	7e
9	water	$k-\epsilon$	2.3 m/s	Colonization with a group of 3 mussels of 1 cm	2D	7f
10	water	$k-\omega$ SST	2.3 m/s	Barnacles: Medium height and medium density	2D	8a;9a
11	water	LES	2.3 m/s	Barnacles: Medium height and medium density	2D	8b;9c
12	water	$k-\omega$ SST	2.3 m/s	Barnacles: Medium height and medium density; Real shape	2D	9b
13	water	LES	2.3 m/s	Barnacles: Medium height and medium density; Real shape	2D	9d
12	water	$k-\omega$ SST	2.3 m/s	Barnacles: Medium height and medium density; Real shape	3D	10b

In this study, two types of structure are studied: an airfoil and a Darrieus vertical axis tidal turbine. Simulations are run in 2 dimensions (2D) excepted in part III-B6 where three-dimensional (3D) simulations have been performed. The characteristics of the airfoil are similar to the ones used in [1] and [2] who estimated impact of barnacles on hydrodynamics around an airfoil using physical and numerical modelling. Authors used a NACA 4424 profile with a chord of 20 cm. The

thickness is by consequence 4.8 cm and numerical simulation are made with an angle of attack of 15° . The tidal turbine is the prototype at 1/5 scale studied several times by [25], [17] and [18] using measurements or simulations. The turbine is composed of three straight blades with a NACA 0018 profile warped on circular blade path. The chord of each blade is 32 mm. The diameter and the height of the turbine are equal to 175 mm. In these previous experiments and simulations,

the input velocity is 2.3 m/s or 2.8 m/s. The same velocities, which are typical values of current velocities in area where tidal turbines are installed, are used during our simulations. The mesh is adjusted to turbine movements with a dynamic mesh. A part of the mesh located in a circle around the blades rotates at the angular velocity ω and the other parts of the mesh are still fixed.

Two sessile benthic organisms are studied: barnacles and mussels. Barnacles are triangular in sections III-B from 1 to 4

and in section III-C. A more realistic shape is used in sections III-B 5 and 6 based on in-situ samplings [15]. Mussels are represented in case of fully coverage with an added thickness and rounded shapes at the surface. In case of isolated mussels, mussel shape is idealised following a NACA profil.

Before to simulate benthic colonization on a tidal turbine, biofouling is modelled on one only blade for simplification. The different scenarios simulated are described in table I.

III. RESULTS AND DISCUSSIONS

A. Clean tidal turbine

The first step consists of validating the model developed for this study by comparison with measurements from [17] available for a clean tidal turbine. They measure Z-vorticity fields using a PIV around blades of a tidal turbine similar to our modelled turbine for different angles with an input current of 2.8 m/s. Figure 1 shows Z-vorticity fields modelled around the tidal turbine for a tip speed ratio of 2. A $k-\omega$ -SST is used.

This pattern is compared to Z-vorticity fields measured by [17]. In general, the model reproduces the fields of Z-vorticity measured. Patterns measured are particularly well reproduced for angles between 0° and 60° and between 240° and 340° . The main differences are observed for angles between 100° and 140° with a vortex modelled in the inner part of the blade which are not observed because the wake flow is very unstable over time.

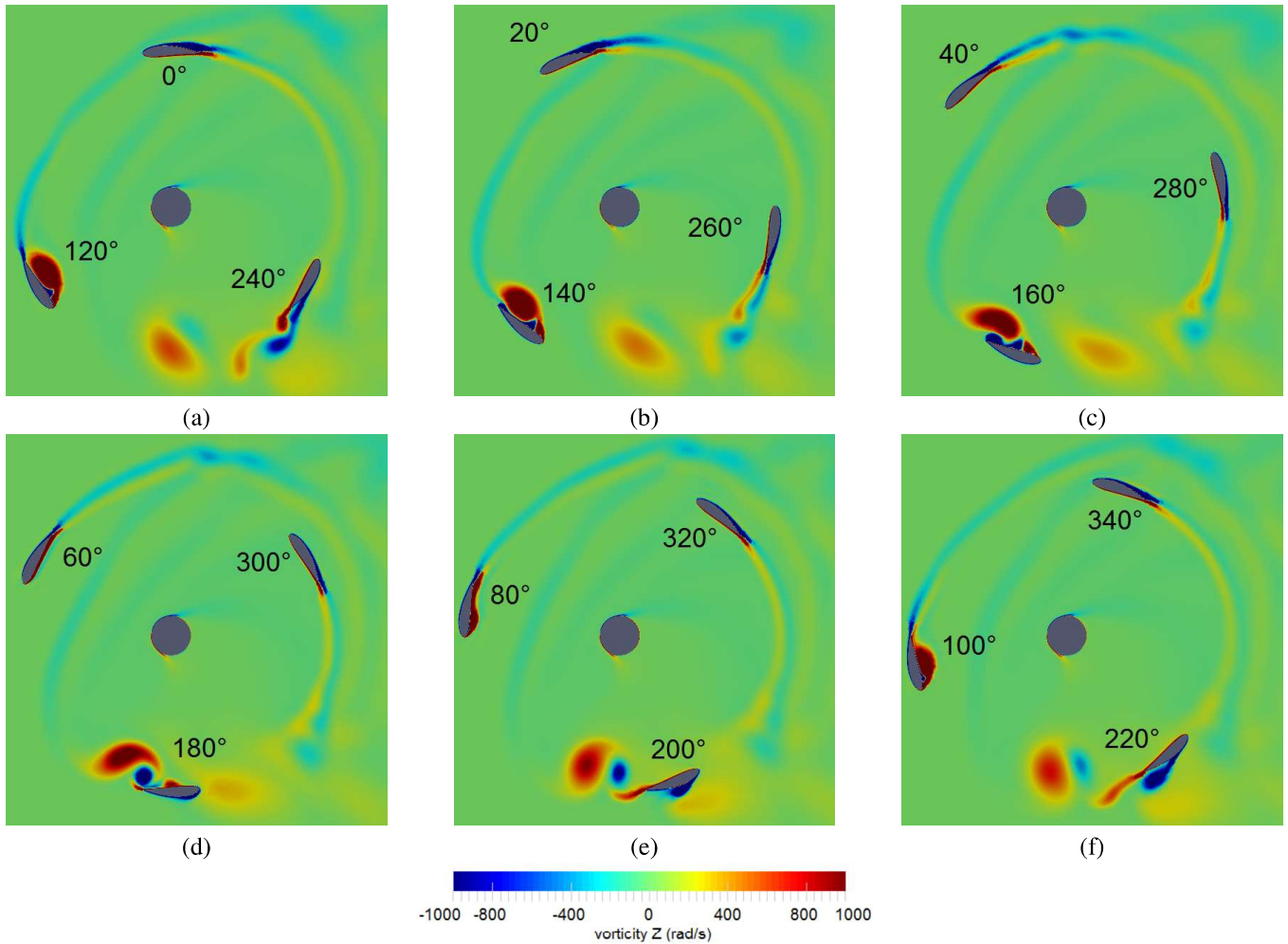


Fig. 1. Numerical Z-vorticity for a tip speed ratio of 2. Angles are indicated for comparison with measurements of [17].

Z-vorticity fields modelled are then compared to simulations made by [18] for several tip speed ratios λ (Fig. 2) with an input current velocity of 2.8 m/s. Rotating axis of tidal turbine is removed in the following simulation. For $\lambda = 1$, vortices simulated around the blades are very similar to those by [18] and located at the same location. For $\lambda = 2$, which is already compared in the previous paragraph with measurements,

general patterns are similar. The main difference is observed close to the blade located at $\theta = 90^\circ$ where a vortex starts to appear. This difference was already visible in the comparison with measurements in the previous paragraph. For $\lambda = 3$, the blade wake becomes a wide filament in the studied model as in [18]. Vortices are delayed by the rotation speed.

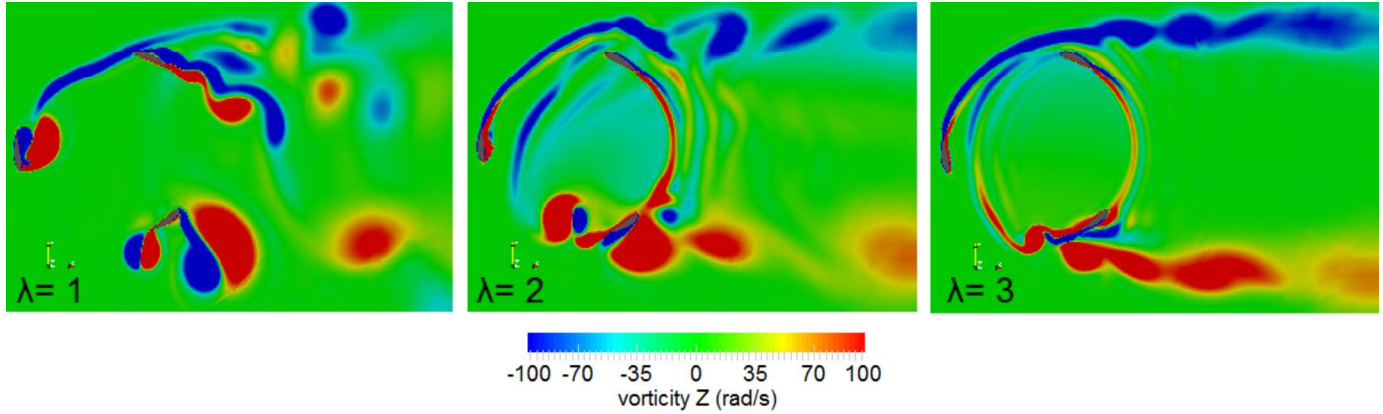


Fig. 2. Numerical Z-vorticity in this study for a tip speed ratio of $\lambda = 1$, $\lambda = 2$ and $\lambda = 3$.

In the previous paragraphs, $k-\omega$ -SST turbulence is used. $k-\epsilon$ turbulence model is now tested. Figure 3 shows results with an input current velocity of 2.3 m/s using $k-\omega$ -SST and $k-\epsilon$ turbulence models.

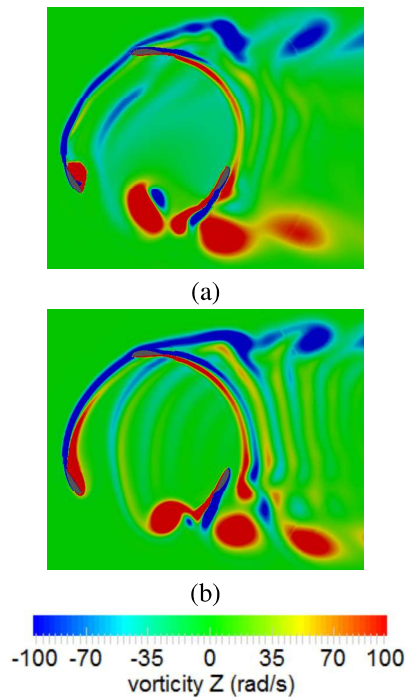


Fig. 3. Numerical Z-vorticity around a tidal turbine using a $k-\omega$ -SST (a) and $k-\epsilon$ turbulence model (b).

Difference is clearly observed between both models (Fig. 3-a and 3-b) close to the blade located at $\theta = 120^\circ$. It is especially for this range of angles that the results from the simulation differ from measurements (Fig. 1). It is expected that $k-\omega$ -SST model performs better under adverse pressure gradient conditions than $k-\epsilon$ model [23]. Here $k-\epsilon$ model seems to give better results close to the blade. However pressure gradient is modified at each blade location during a rotation of tidal turbine. This could change typical turbulence model performances. Turbulence model plays a key role and further investigations are needed.

B. Biofouling on one only blade

1) *Comparison model-measurements:* Influence of barnacles on hydrodynamics around an airfoil was previously experimented by [1] and modelled by [2]. They investigate the lift to drag ratio in the air for several sizes and density of barnacles. This ratio should be maximised for optimum performance. Our first simulations take place in the air to be able to compare these results with these experiments and modellings. Even if air and water are two very different fluids, they could respond in a similar way for geometrically similar objects using a Reynolds similarity. The input velocity in the air is 34 m/s, which correspond to 3.4 m/s in the water with Reynolds similarity. The turbulence model is $k-\epsilon$ because former used that. Three heights of barnacles (0.7, 3.2 and 5.7 mm, minimal, medium, maximal respectively) and three densities (11389, 21389 and 42253 barnacles per m^2 , weak, medium, strong respectively), observed by [1], are tested (Fig. 4). The height and the density of barnacles clearly influence this ratio. The lift to drag ratio reduces progressively with the increase of height (Fig. 4-a). The reduction of the lift to

drag ratio with the barnacle density is strong from the minimal density. When the density increases, this ratio remains constant (Fig. 4-b). Our simulations reproduced these tendencies well. Differences are observed for the minimal height and density of barnacles because of our too coarse mesh near the wall to simulate the very small scale processes in that case. However, if we refine again the mesh near the wall, simulations become unstable. Our results and previous studies ([1], [2]) show that sensitivity to species height is more important than the sensitivity to density. Lift to drag ratio is greatly reduces from medium size.

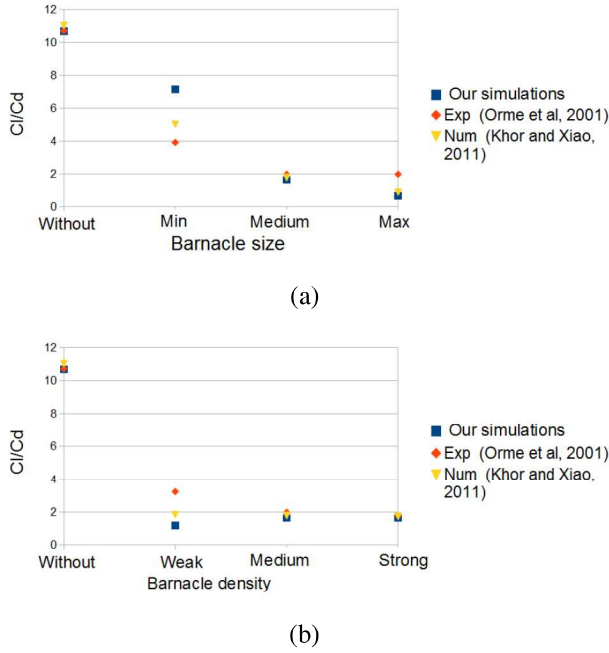


Fig. 4. (a) Lift to drag ratio for various barnacle size. Density is 21389 barnacles per m^2 . (b) Lift to drag ratio for various barnacle density. Barnacle height is 3.2 mm.

2) *Influence of the fluid:* Z-vorticity around a blade located in water colonized with a medium height and density of barnacles with an input velocity of 2.3 m/s (as used in experiments of [17]) is compared to Z-vorticity around the same colonized blade located in air with an input velocity of 23 m/s (Fig. 5) which corresponds to a Reynolds similarity. Patterns of Z-vorticity are similar but their intensities differ. The intensity of Z-vorticity is stronger in the air than in the water because air viscosity is weaker than water viscosity [26].

3) *Sensitivity to turbulence models:* Two turbulence models (RANS $k-\omega$ SST and LES Smagorinsky) are tested with the blade colonized with a medium height and density of barnacles (Fig. 6). The result obtained with the $k-\epsilon$ model is presented Fig. 5-b. The level of details varies depending of the turbulence model used. No eddy separates from the blade's surface with

$k-\epsilon$. Eddies separate from the blade's surface with $k-\omega$ SST models and move two by two in the wake because $k-\omega$ is used near the wall. The flow is also stable along the intrados of the blade with no eddy separation. Similar results are found with more details with LES. Smaller eddies are observed. However the flow is not stable along the intrados and small eddies separate.

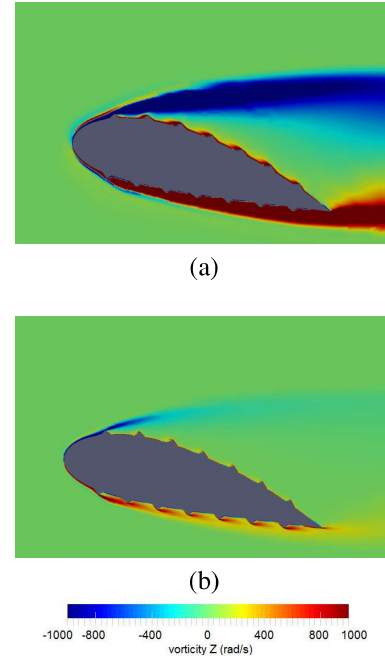


Fig. 5. Numerical Z-vorticity around a blade colonized with a medium height and density of barnacles located in the air (a) and in the water (b).

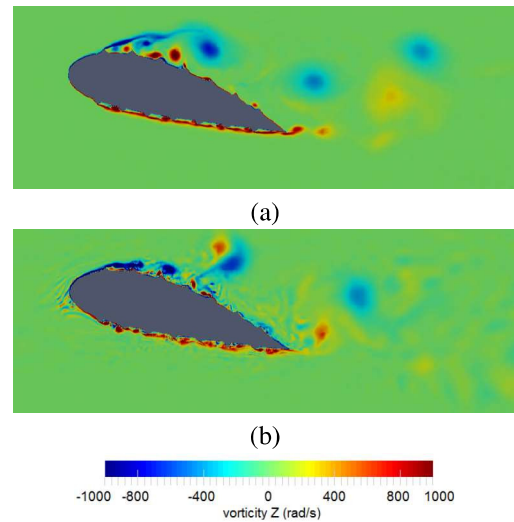


Fig. 6. Numerical Z-vorticity around a blade colonized with a medium height and density of barnacles using (a) $k-\omega$ SST and (b) LES turbulent model.

4) *Sensitivity to species density, height and shape:* Fig. 7-b shows the blade fully covered by barnacles (i.e. without any free spaces between barnacles) with a medium height and can be compared to the clean blade (Fig. 7-a) and to the blade colonized by medium height and density of barnacles (partial colonization, Fig. 5-b). The behaviour of the fluid is different between the partial (Fig. 5-b) and the fully (Fig. 7-b) colonization of the blade. In the partial colonization, the first barnacle located on the blade leads to a flow separation (Fig. 5-b). In the fully colonized blade (Fig. 7-b), flow separation occurs further (6th-7th barnacles). The flow seems to be smoothed by the roughness of the first barnacles. The pattern of Z-vorticity is more similar between the fully colonized (Fig. 7-b) and the clean blade (Fig. 7-a) than between the partially colonized (Fig. 5-b) and the clean blade. A fully colonization is like an increase of the blade thickness and therefore little changes in hydrodynamic are observed in comparison to the clean blade. A partially colonization breaks the shape and creates flow separation near the benthic organisms.

colonized by mussels (i.e. without any free spaces between mussels) of 0.7 and 1 cm, respectively. The pattern of Z-vorticity is close to Z-vorticity for a clean blade with however a separation point located more at the left side. Stronger Z-vorticities are still closer to the wall with mussels than with barnacles due to the shape. The angular form of barnacles interacts more with the fluid than the rounded mussels which modify less. When three mussels are fixed between barnacles (Fig. 7-e), the modification of Z-vorticity field is small: even if the shape is different, the mussels are located downstream the flow separation and therefore have a little impact on the flow. When a group of three mussels is located upstream a separation point (Fig. 7-f), this small quantity of mussels could have stronger impact than a fully colonisation. The same three mussels located downstream of the separation point at the top of the blade have no impact on hydrodynamics (not shown here). In our simulation, the size of mussels doesn't influence the pattern of Z-vorticity (Fig. 7 c-d), Z-vorticity fields are just shifted because of the difference of the thickness of mussels.

Fig. 7-c and 7-d show the Z-vorticity when the blade is fully

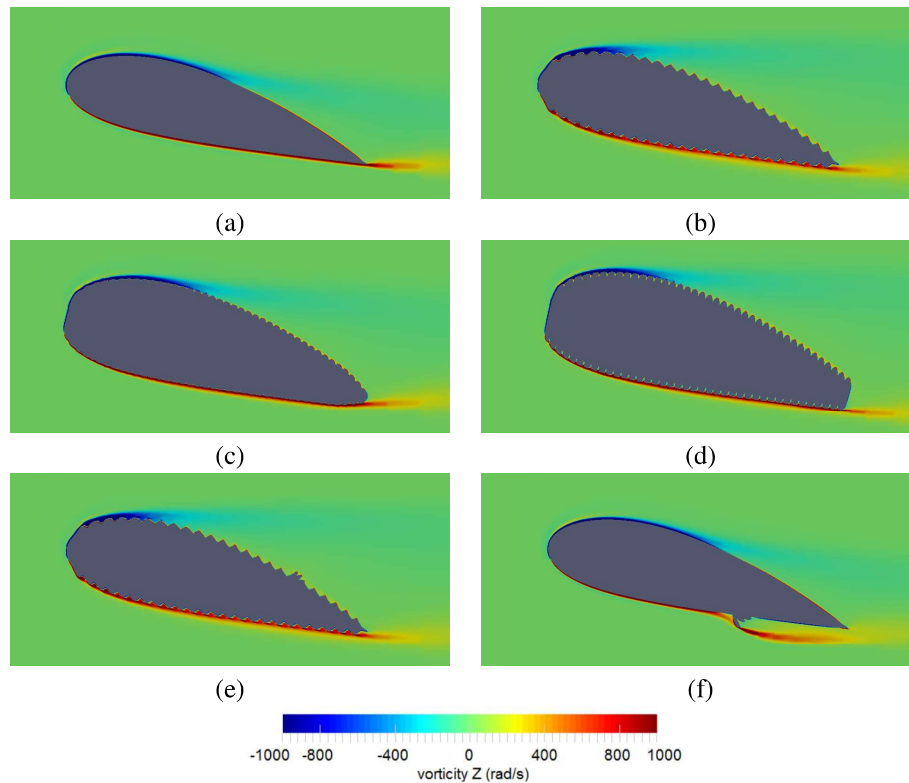


Fig. 7. Numerical Z-vorticity around a blade in water without colonization (a), fully colonized (b,c,d,e) and colonized with only a group of 3 mussels of 1cm height (f). (b) is for the blade with medium barnacles. (c) et (d) are for the blade with mussels of 0.7cm and 1cm height, respectively. (e) is for the blade with medium barnacles and a group of 3 mussels of 1cm height.

5) *Sensitivity to barnacle geometry:* Previously, barnacles were modelled using a triangular shape which is close to barnacle outline. However, barnacle shape is more complex in reality [15]. A geometric model of barnacles are created with

Blender from observations of barnacles sampled in Cherbourg bay. Outlines of this model under different angles are added on the studied NACA 4424 profile with the same height and density as in paragraph III-B3. RANS $k-\omega$ SST and

LES Smagorinsky turbulence models are used. Geometry of barnacles modifies vorticity with both models. With the $k-\omega$ SST model, vortices shed at the intrados side when barnacle shape are more realistic (Fig. 8-b) . This was not observed with idealized barnacles (Fig. 8-a). When LES model is

used, vortices oriented in both directions are simulated along intrados with realistic barnacles, whereas all the eddies are anticlockwise with idealized barnacles.

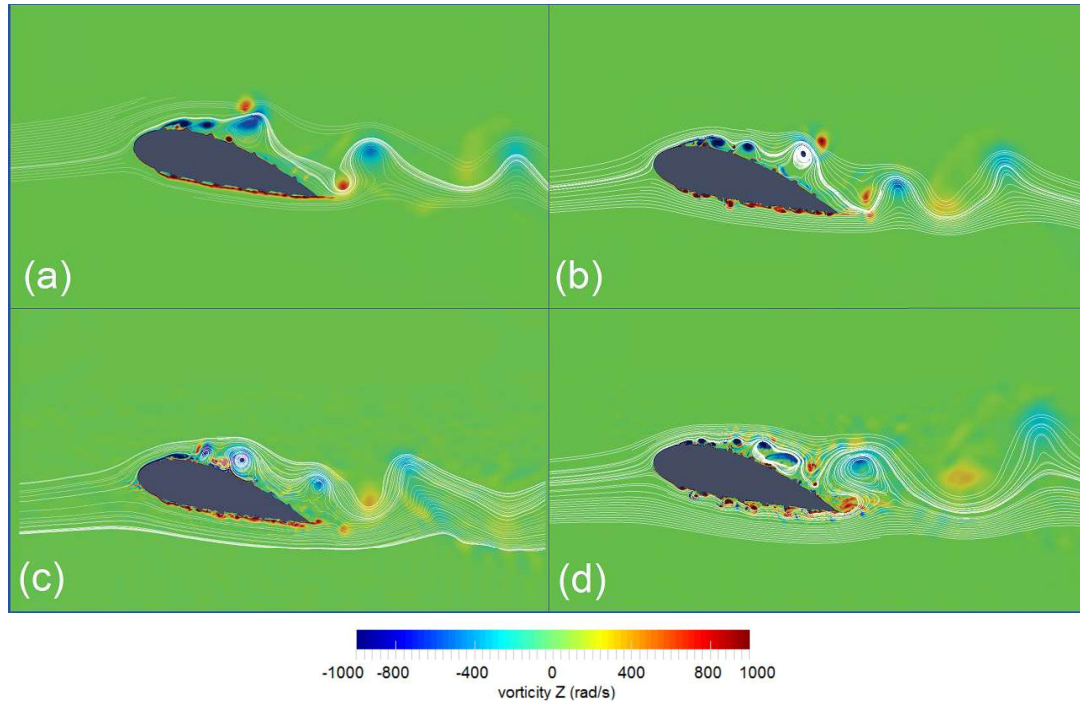


Fig. 8. Numerical Z-vorticity around a blade colonized with barnacles having idealized (a,c) and real shape (b,d) using $k-\omega$ SST (a,b) and (c,d) LES turbulent model.

6) *Sensitivity to 3D effects:* A simulation is made in 3D to investigate 3D effects of barnacles colonization using $k-\omega$ SST model. The blade thickness is 2 cm and divided by a number of cells between 10 and 80. The shape of barnacles is reproduced as in the previous paragraph from observations of specimens sampling in the Cherbourg bay in 2015 [15]. Fig. 9-a shows the location of barnacles on blades. No eddy is visible in 3D simulations (Fig. 9b) whereas eddies are visible in 2D using $k-\omega$ SST model (Fig. 3-b). The 3D mesh was chosen coarser than the 2D mesh in order to keep reasonable computing cost. This difference of mesh can explain the presence or not of eddies. Barnacles create localized recirculation cells. Flow varies slightly in the third direction away from the barnacles (not shown). This simulation is computationally expensive.

C. Colonized tidal turbine

Fig. 10 compares the Z-vorticity between a clean and a colonized tidal turbine. The input velocity is 2.3 m/s and the $k-\omega$ -SST turbulence model is used. Idealized shape of barnacles are used. The size of the barnacles is 0.7 mm on a blade with a thickness of 5.8 mm, so it represents 12% of the blade thickness. This percentage corresponds to the maximal height of barnacle studied on the only blade.

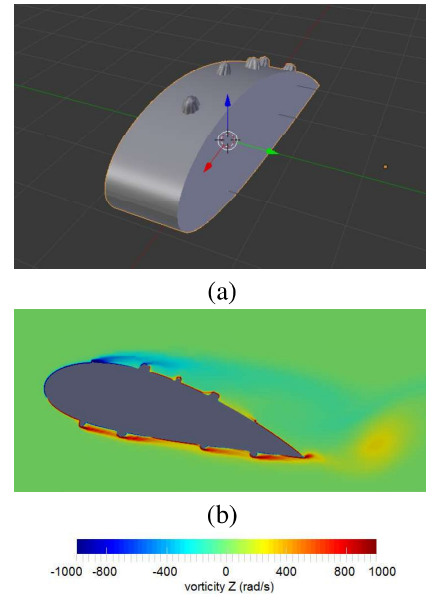


Fig. 9. (a) Geometry of a 3D blade colonized by barnacles and (b) numerical Z-vorticity around it along axis where barnacles are fixed.

In general, the intensity of vorticity is stronger close to the blade. A vortex appears because of the biofouling at the inner part of the blade located at $\theta = 60^\circ$. Vortices are created in the wake of rotating blades and in particular downstream to it and to the blade located at $\theta = 300^\circ$. These simulations showed that hydrodynamic is clearly modified by barnacles.

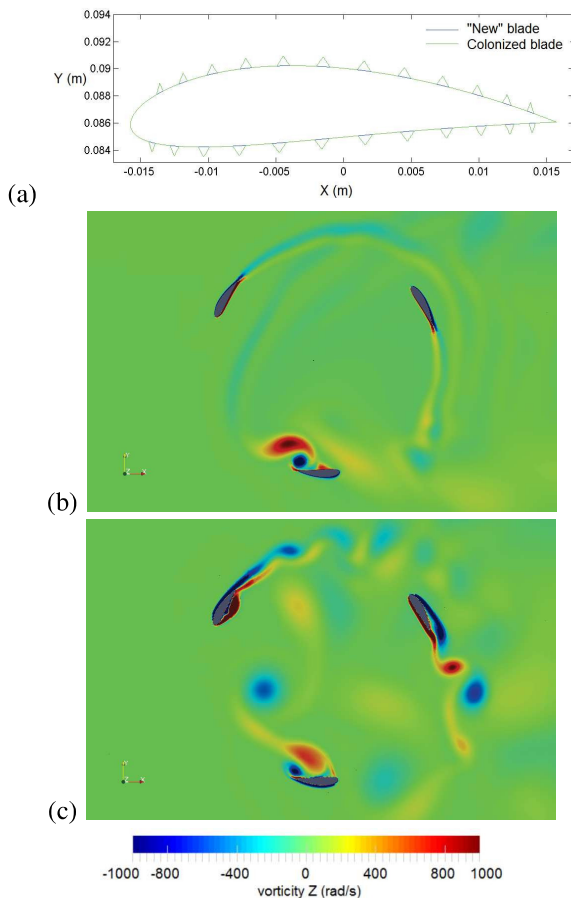


Fig. 10. (a) Geometry of the clean blade (blue line) and the blade colonized by barnacles (green line). Numerical Z-vorticity around a tidal turbine (b) with new clean blades and (c) with colonized blades by idealized barnacles.

IV. CONCLUSION

Our simulations show that benthic organisms fixed on a blade or a tidal turbine clearly modify hydrodynamic around it and could reduce performance. Sensitivities to different shapes, heights and densities of species were tested. In case of partial colonization, vorticity fields are more sensitive to species height than to density. In case of full colonization, height of species does not have a significant impact. The location of the benthic organism compared to the separation point is primary. A single organism located upstream to this point could have a stronger impact than several organisms located downstream. Modelled flows around structures are very sensitive to turbulence models chosen. Pattern of vorticity seems more detailed around a colonized blade with $k-\omega$ -

SST and LES model (with eddies separation) than with $k-\epsilon$ model. However results with $k-\epsilon$ model were closer to measurements for particular angles in case of a clean tidal turbine. Comparison with measurements around colonized structures is needed to choose the best turbulence model. Simulation in 3D shows 3D-effects of barnacles on flows. Simulations with several barnacles arrangements could be interesting but in-situ measurements are previously required to simulate realistic conditions. Finally a colonized tidal turbine was investigated. Barnacles fixed on blades produce vortices and modify clearly hydrodynamic. The next step will be to assess the impact of these modifications on performances. At the same time, efforts should be focused on turbulence modelling with the implementation of a new hybrid RANS-LES model to allow accurate three-dimensional simulations while minimizing the computing cost.

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