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I would like to thank Professor Alberto Aliseda for his help all along this project, and for always giving good advices. But what I mainly would like to thank him for is allowing me to come here and work on this very interesting subject that Tidal energy is.
I also thank my tutor Teymour Javaherchi for his patience and kindness. He was always ready to explain or answer to my numerous questions, and helped me understanding the research methodology.

Finally I thank all the team for its warm welcome.

Numerical study of Horizontal Axis Hydrokinetic Turbines: performance analysis over a 7° pitch angle blade

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REFERENCES

I – Introduction

1) Tidal energy

Tidal power is a quite new way to produce electricity, by extracting the power from the marine currents. Engineers have started to develop this technology approximately one decade ago: Verdant Power (New York, 2000), Openhydro (Ireland, 2005), Sabella (France, 2008)… This effort is made during a climate of increasing awareness of the global need for research and development in renewable energy.

This technology can be compared to the wind power technology. Indeed, it uses an incoming flow to make the blades of a turbine rotate, and this mechanical energy is converted into electricity thanks to an alternator. The main difference is that the fluid density is much higher for tidal turbines: indeed sea water is about 850 times denser than air. The available power for a V averaged velocity water flow across a turbine is given by:

$$P = \frac{1}{2} * \rho * A * V^3$$

where A is the surface of the turbine disk. Since the water is very dense, a slow water flow of only few meters per second can result in the same power as an air flow with a much higher velocity across a wind turbine.

But there are some new disadvantages which have to be taken into account, like the erosion issue caused by the sea water, and also its installation and maintenance require a lot of equipment. Without saying that the device often has to be settled hundreds of meters deep…
Another phenomenon proper to this immerged technology: the cavitation. Happening when pressure close to the blade is too low, it can have very bad consequences on the performances of the turbine, so it must be limited as much as possible. Some studies are also carried out to see if the pressure drop caused by the device can have a negative impact on the health of the fishes going through it.

According to the formula giving the power, the velocity is the main parameter considered when choosing the place where the device should be located. The high velocity regions are of course often the best fitted for the tidal turbines sites.
The Puget Sound is a place of choice to test tidal devices, thanks to its high velocity fields regions. Some studies are currently done to optimize the location of these devices.

The main work also consists in designing the best shape for the blade, which implies a good choice of the hydrofoils used, and also the twist and pitch angles. These characteristics are very important because it will determine the lift and drag forces over the blade, and therefore the efficiency of the turbine. This study will focus especially on the blade pitch influence, for different flow conditions (represented by the Tip-Speed-Ratio).

2) A little about the Tip-Speed-Ratio

The Tip-Speed-Ratio is of a very important matter in the study of Hydrokinetic turbines. Mostly because it has a direct consequence on the Angle of Attack (AoA) distribution along the blade. Its definition is:

$$TSR = \frac{R\omega}{V_\infty}$$

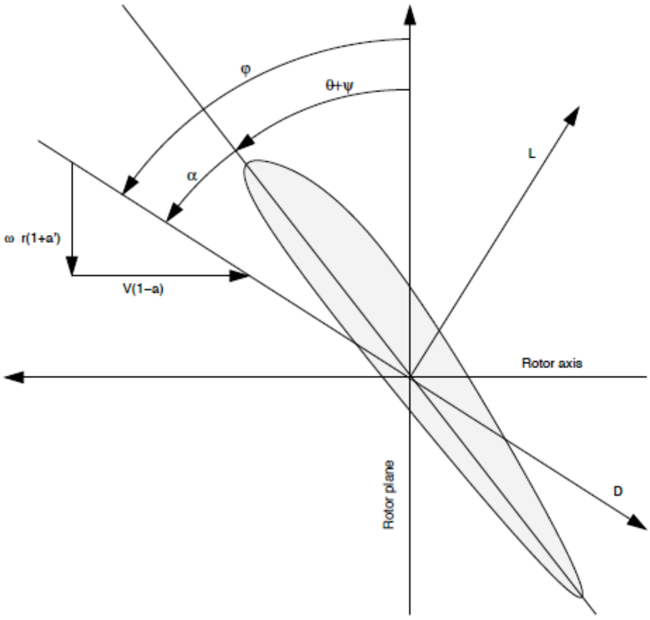
where $R\omega$ is the rotational speed at the tip of the blade (R is the radius) and V_∞ is the free stream velocity.

Let's consider the local ratio $\frac{r\omega}{V_\infty}$ where r is the varying distance from the hub. For one given TSR value, the range of values that this ratio will take along the blade is fully known (only r is changing). This ratio is appearing in the AoA formula, as follow:

$$AoA = \tan^{-1}\frac{V_\infty}{r\omega} - \theta - \psi$$

where ψ is the twist which is varying from the root to the tip, and θ which is the blade pitch. On the following picture, the angle between the flow direction and the rotational plane is:

$$\varphi = \tan^{-1}\frac{V_\infty}{r\omega}$$



If the TSR decreases, the ratio $\frac{V_\infty}{r\omega}$ is globally increasing so the incidence of the flow (and the AoA) is also increasing.

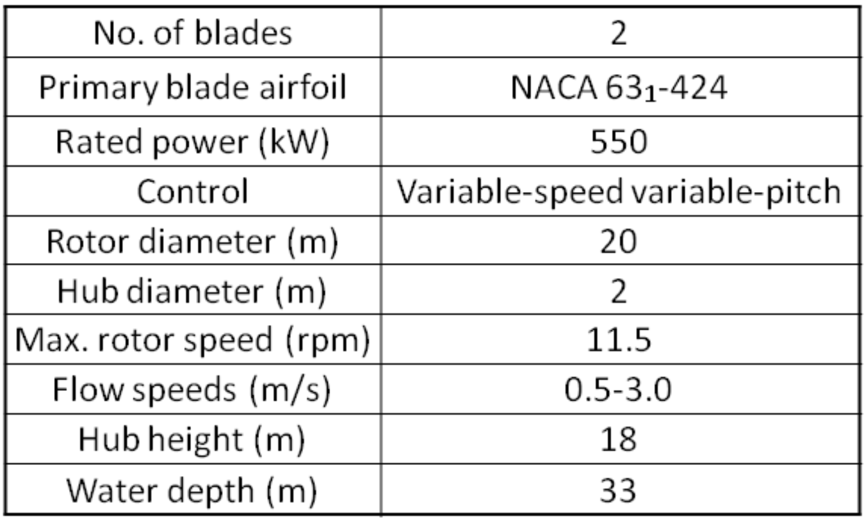
Increasing the TSR can be a good thing since it is increasing the AoA and therefore the lift coefficient. But this is true provided that the AoA hasn't reached its critical value where the separation from the blade is happening. This phenomenon is most likely to appear at the root, where the biggest AoA values are concentrated.

According to the AoA formula, a high incidence between the flow direction and the rotor plane (φ) can be compensated by a bigger value of the blade pitch θ. **Increasing the pitch when the TSR is decreasing allows to avoid too high AoA values and therefore separation.**

3) Turbine Blade Design

We consider a hypothetical 550 KW turbine intended for deployment in the Northern Admiralty Inlet of Puget Sound in Washington State. The mean water velocity is approximately 1 m/s, although velocities as high as 3 m/s occur during the tidal cycle.

The design and operating specifications for the turbine are presented in Figure 1:



No. of blades	2
Primary blade airfoil	NACA 63_1-424
Rated power (kW)	550
Control	Variable-speed variable-pitch
Rotor diameter (m)	20
Hub diameter (m)	2
Max. rotor speed (rpm)	11.5
Flow speeds (m/s)	0.5-3.0
Hub height (m)	18
Water depth (m)	33

Figure 1:design and operating specifications

The blade design was optimized for a variable-speed variable-pitch (VSVP) turbine with a maximum rotation rate of 11.5 rpm. The NACA6-0240 (or NACA 63-424) was chosen as the primary shape for the turbine blade.

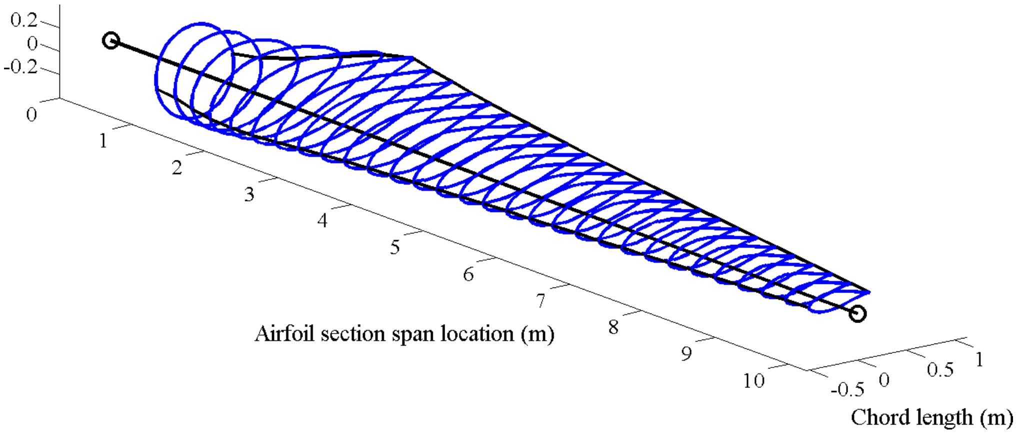


Figure 2: turbine design and its hydrofoils

The optimization objective for the blade design process was to maximize power generation over a range of flow speeds from 0.5 m/s to 3.0 m/s. Within this range of flow speeds, the design software determined the rotor's rotation speed and the blade's pitch angle. The optimization algorithm bounded the turbine's maximum power output at 550 kW and also avoided cavitation.

XFOIL was used to predict the NACA 63(1)-424 airfoil's lift, drag, and pressure coefficients used for the blade element momentum analysis.

4) Previous work

In the previous work [3], the 0° pitch angle case was studied for different tip speed ratios: 7, 6.7 and 6.3. They were tested with two different turbulence models: Spalart Allmaras and K-ω. After being validated, these models were used for the study of an array of turbines. This study is developed in M.Tessier and N.Tomasini's report.

5) Study of the blade with a 7° blade pitch

The full study of the turbine should ideally be done for every flow conditions, i.e. for the range of Tip-Speed-Ratio (TSR) that the device might be confronted to.
The optimization table (figure 3) is giving the matching values between the TSR and the blade pitch that should be used.

What is necessary now is to test on Fluent these TSR values with the matching blade pitch, to check if it is truly an optimized choice. So Fluent is used to validate the optimization table. Indeed Fluent is supposed to be an accurate way to get the velocity field, by solving the Navier-Stokes equations at every node of the mesh.

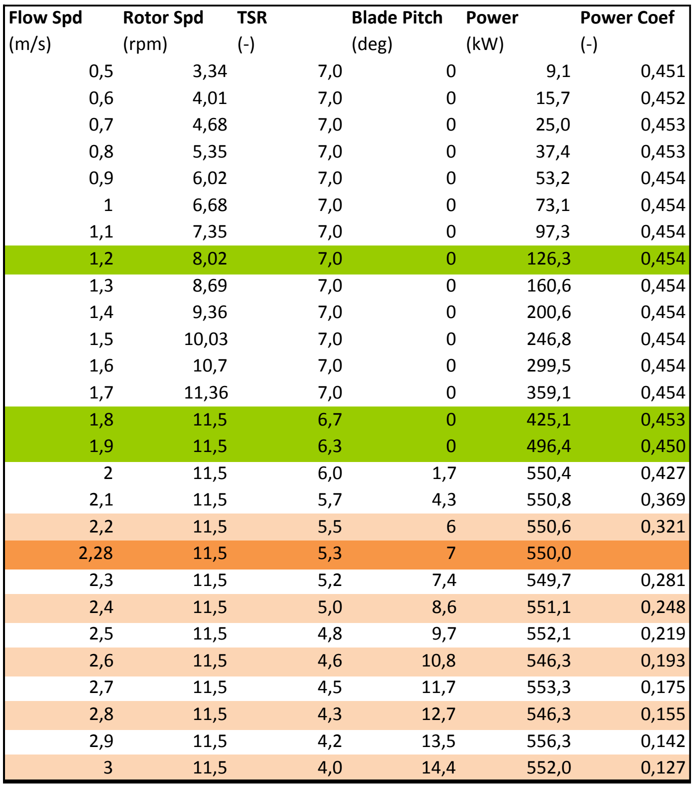
But testing different blade pitch values on Fluent implies modifying the mesh several times, which is quite time consuming! Therefore, it had been first decided to test it for a blade pitch value which would allow a little change of TSR downward. This way we can extend our study from one TSR value (the one given by the table) to a certain range of TSR whose values are close to the first one.

On the following table, the green lines are the one previously studied. We chose to study the following conditions:

- 7° blade pictch
- TSR = 5.3

So 5.3 is supposed to be the best fit for this blade pitch. But we see that we can also test this geometry with higher TSR, since the AoA distribution will be lower.

Finally, lower TSR values will also be tested, to see how the flow behaves at these supposedly "bad conditions".



Flow Spd (m/s)	**Rotor Spd** (rpm)	**TSR** (-)	**Blade Pitch** (deg)	**Power** (kW)	**Power Coef** (-)
0,5	3,34	7,0	0	9,1	0,451
0,6	4,01	7,0	0	15,7	0,452
0,7	4,68	7,0	0	25,0	0,453
0,8	5,35	7,0	0	37,4	0,453
0,9	6,02	7,0	0	53,2	0,454
1	6,68	7,0	0	73,1	0,454
1,1	7,35	7,0	0	97,3	0,454
1,2	8,02	7,0	0	126,3	0,454
1,3	8,69	7,0	0	160,6	0,454
1,4	9,36	7,0	0	200,6	0,454
1,5	10,03	7,0	0	246,8	0,454
1,6	10,7	7,0	0	299,5	0,454
1,7	11,36	7,0	0	359,1	0,454
1,8	11,5	6,7	0	425,1	0,453
1,9	11,5	6,3	0	496,4	0,450
2	11,5	6,0	1,7	550,4	0,427
2,1	11,5	5,7	4,3	550,8	0,369
2,2	11,5	5,5	6	550,6	0,321
2,28	11,5	5,3	7	550,0	
2,3	11,5	5,2	7,4	549,7	0,281
2,4	11,5	5,0	8,6	551,1	0,248
2,5	11,5	4,8	9,7	552,1	0,219
2,6	11,5	4,6	10,8	546,3	0,193
2,7	11,5	4,5	11,7	553,3	0,175
2,8	11,5	4,3	12,7	546,3	0,155
2,9	11,5	4,2	13,5	556,3	0,142
3	11,5	4,0	14,4	552,0	0,127

Figure 3: Optimization table for the DOE model

The TSR values tested in this study are: 6, 5.5, 5.3, 5, 4.6, 4.3 and 4

II – Methods

1) Description of the geometry

As seen in the Turbine Blade Design section, the original geometry is the DOE blade model, which was designed by the NREL in Colorado. The design software (WT_Perf) relies on the BEM (Blade Element Momentum) theory.
The resulting design is meant to be optimized for the different flow conditions.

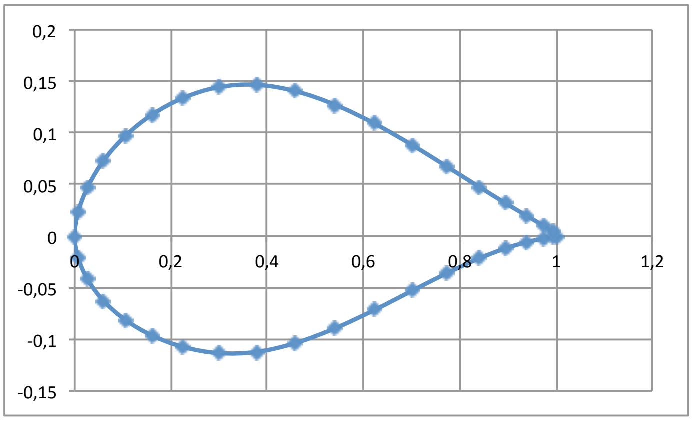
The geometry used in this study is a modified version of the original DOE model. Indeed it was previously decided to cut the root of the blade at the radius of 2.8m (whereas the starting radius of the blade was 1m before). The hub was therefore enlarged from 1 to 2.8m.

This modification was motivated by the fact that the root of the blade was creating separation of the flow, and the created turbulence at this region was causing a very long time of calculation. It was estimated that cutting the root at 2.8m would reduce a lot this calculation time, and modifying the power only by 3%. Of course we must remind of these 3% power change when considering the study of the whole blade.

Blade Geometry							
r/R	**Radius**	**Pre-Twist**	**Chord**	**% Thick**	**Thickness**	**PitchAxis**	**profile coordinates filename**
(-)	(m)	(deg)	(m)	(t/c)	(m)	(x/c)	(-)
0,115	1,150	12,860	0,800	100	0,80	0,50	NACA6_1000.prof
0,145	1,450	12,860	0,894	86,4	0,772	0,48	NACA6_0864.prof
0,175	1,750	12,860	1,118	62,9	0,703	0,44	NACA6_0629.prof
0,205	2,050	12,860	1,386	44,4	0,615	0,38	NACA6_0444.prof
0,235	2,350	12,860	1,610	32,9	0,530	0,34	NACA6_0329.prof
0,265	2,650	12,860	1,704	27,6	0,470	0,32	NACA6_0276.prof
0,295	2,950	11,540	1,662	25,9	0,430	0,32	NACA6_0259.prof
0,325	3,250	10,440	1,619	24,7	0,400	0,32	NACA6_0247.prof
0,355	3,550	9,500	1,577	24	0,378	0,32	NACA6_0240.prof
0,385	3,850	8,710	1,534	24	0,368	0,32	NACA6_0240.prof
0,415	4,150	8,020	1,492	24	0,358	0,32	NACA6_0240.prof
0,445	4,450	7,430	1,450	24	0,348	0,32	NACA6_0240.prof

Figure 4: a part of the geometry table: the blade was cut in the middle of the 2.65 and 2.95m radii

The hydrofoils are now limited to the number of 3, and they have a good geometry (figures 5,6,7)



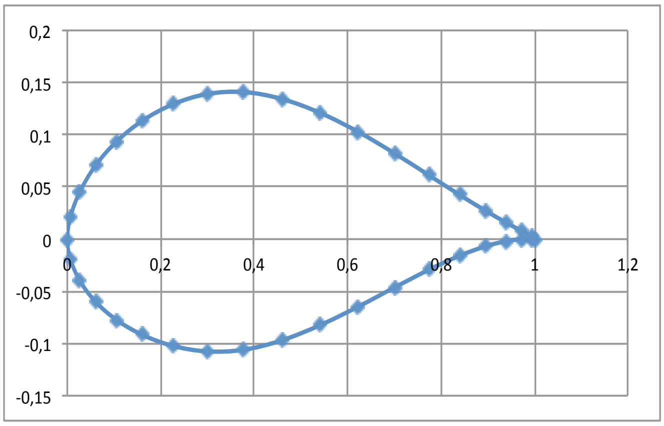


Figure 5: section n°2 → NACA6-0247

Figure 6: section n°1 → NACA6-0260

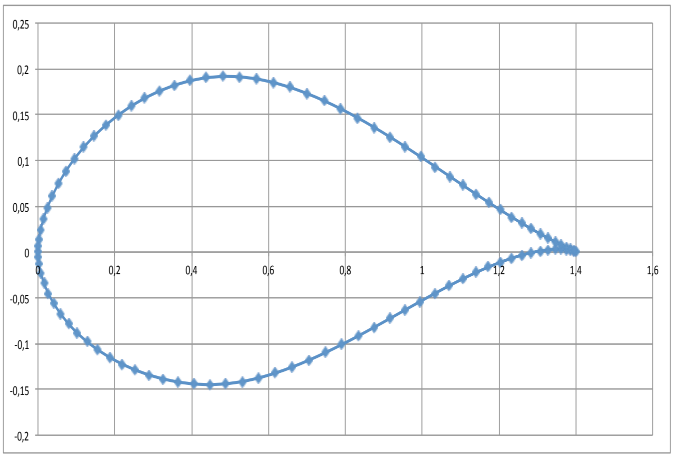


Figure 7: section n°3 → NACA6-0240

2) Meshing on Gambit

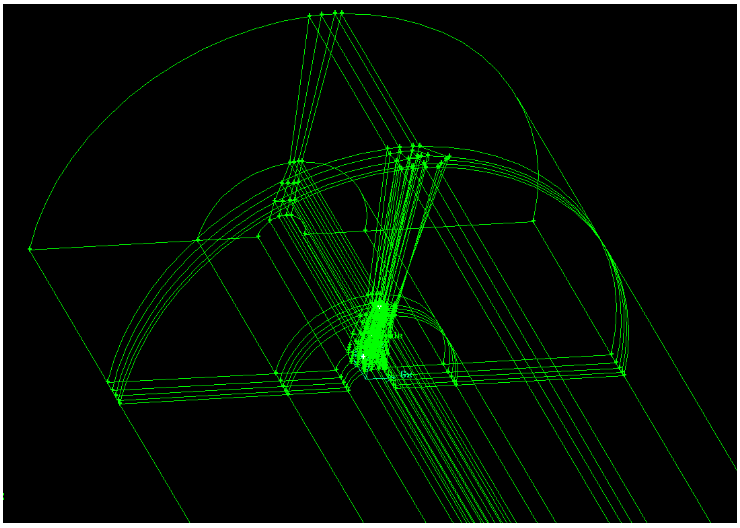


Figure 8: rotated mesh

The meshing on Gambit enables to create a C-mesh around the blade. This very fine mesh is required to capture the boundary layer effects at the blade, since it is the region of interest. We want to report the forces which are acting on it.

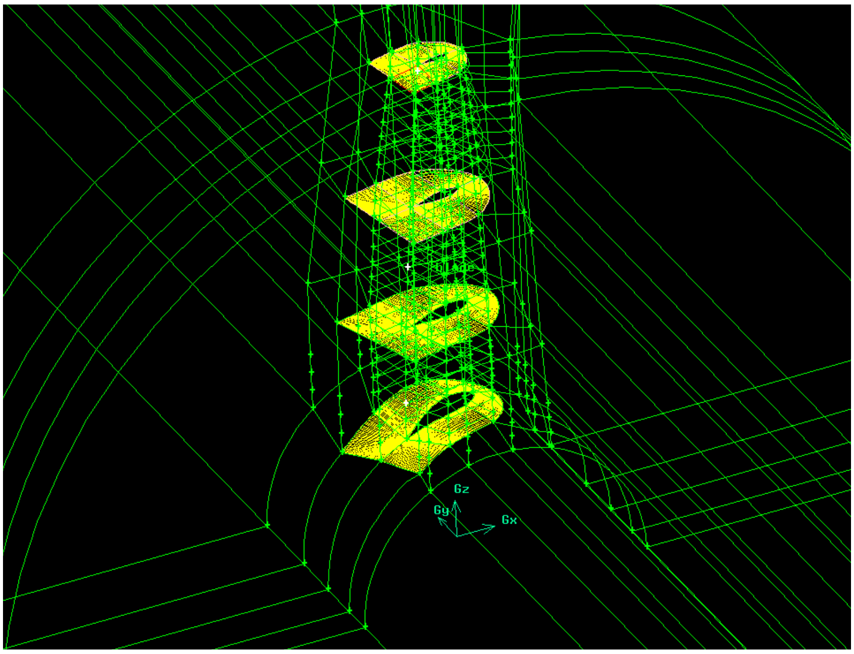


Figure 9: view of the C-mesh

The 0° pitch angle blade mesh was used as a start to create the 7° pitch angle mesh. The principle was to use the previous geometry and to make it rotate of 7° along the Z-axis. After rotating the geometry, the previous C-mesh had to be deleted and the new C-mesh was linked with the rest of the mesh.

The numerical model used for this study is SRF exclusively [1][2].

III – Results

1) Comparison between Fluent and optimization table (WT Perf) results

The 7° pitch angle blade is tested for the different TSR:

TSR	Power SRF – Spalart Allmaras (kW)	Efficiency	Optimization table Power (kW)
6	54	0,1325	not defined
5.5	279	0,1763	not defined
5.3	331	0,1882	550
5	416	0,2028	not defined
4.6	567	0,2173	not defined
4.3	731	0,2244	not defined
4	908	0,2265	not defined

Figure 10: Performances for different TSR values

The power expected for the TSR of 5.3 was 550kW, according to the Optimization table. The first comment on these results is that it is possible to get a better efficiency by decreasing the operating Tip-Speed-Ratio value for this 7° blade pitch. 5.3 might be not the best fitted eventually. The second comment is that this difference with the optimization data should be explained.

To explain these differences, we must take a look at the software used for the optimization data. The data was created by using WT Perf software which relies on the Blade Element Momentum theory.

It makes the calculation by using the hydrofoils data (C_l, C_d, C_p) as an input. To be allowed to compare it to the Fluent data, we give the 3 hydrofoils data (NACA6-0259, NACA6-0247 and NACA6-0240) as the input, instead of the whole blade. Each hydrofoil data was obtained previously by using the XFOIL software, which is a 2D simulation of a flow around the studied hydrofoil.

WT Perf was used to estimate the values of the power we would get for the other TSR values.

TSR	Power SRF – Spalart Allmaras (kW)	Power WT Perf (kW)	Error (%)
6	54	107	99
5.5	279	446	60
5.3	331	505	52
5	416	597	43
4.6	567	764	35
4.3	731	945	29
4	908	1134	25

Figure 11: Comparison of Fluent's and WT Perf's power

First we see that the WT Perf power for 5.3 is not 550kW, but 505kW. This is explained by the fact that we are only testing the blade without the root instead of the whole blade.

Also we see that the error percentage is very high, and that it tends to decrease when decreasing the TSR. To understand these differences we need to look at the AoA, C_l, C_d distributions along the blade for each case.

On Fluent, the C_l and C_d coefficients don't figure among the reported values. It is calculated in an Excel post-processing file, by using the Lift and Drag, which are deduced from the X and Y forces.

$$L = Ycos(\varphi) + Xsin(\varphi)$$
$$D = Ysin(\varphi) - Xcos(\varphi)$$

$$\text{where } \varphi = \tan^{-1}\frac{V_\infty}{r\omega}$$

The X and Y forces are reported in Fluent, but the φ angle is deduced by making our own estimation. Indeed the definition of φ is given by taking the ratio of the incoming flow velocity and the rotational speed $r\omega$. If the incoming flow velocity was here estimated as being V_∞, in reality it is not the case. Indeed, the incoming flow is feeling the presence of the blade as an obstacle so the velocity is decreasing when it gets closer to the blade. The right formula is, therefore:

$\varphi = \tan^{-1}\frac{V_{\text{local}}}{r\omega}$ where V_{local} must be estimated in the most accurate way.

To evaluate it, we processed in the same way as M.Tessier and N.Tomasini (see their report).

So the φ distribution all depends on this V_{local} estimation.

Here is the comparison between the C_l and C_d distributions in the 5.3 case (the other TSR are giving similar observations):

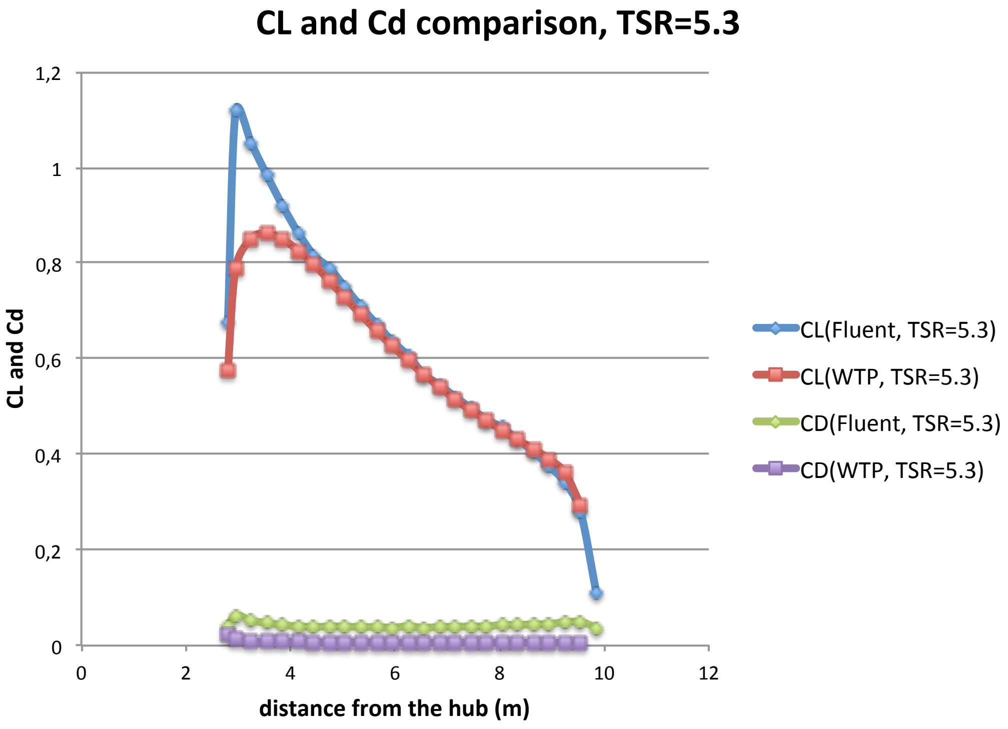


Figure 12: Comparison of the Lift and Drag coefficients distributions along the blade

Now if we look at the Cd and Cl against the AoA distribution:

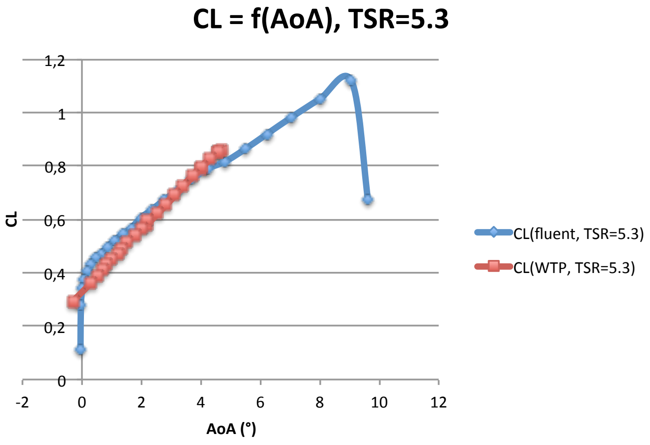


Figure 13: CL comparison when plotted against the AoA

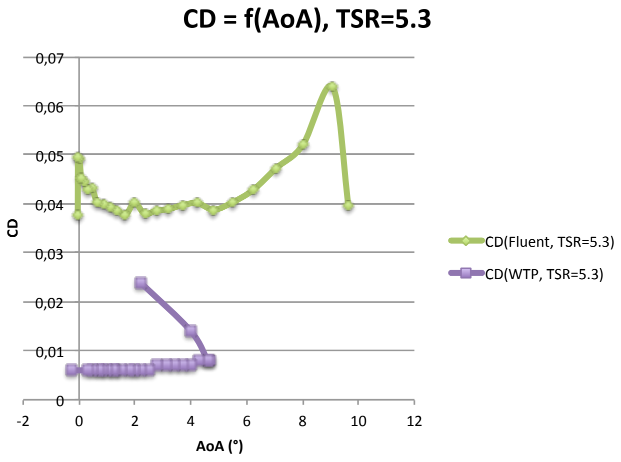


Figure 14: CD comparison when plotted against the AoA

The first thing to notice is that the AoA distributions along the blade are very different. The range of values of WT Perf is generally included in the range of values of Fluent. Also, the drag coefficients are very different, even in the regions where we have the same values of AoA. For example, at AoA = 2° we have Cd = 0.006 for WT Perf whereas Fluent gives approximately Cd = 0.04.

The Lift coefficient doesn't play a pig part in the difference of power. Indeed the main differences are included for the lowest distances from the hub, but yet the torque (partly caused by the lift) is small in this part because of the low values of the distance from the hub. (Let's remind that $T = r * X$ where r is the distance from the hub, X the x-direction force component).

So the main explanation of the difference of power between WT Perf and Fluent is the difference between the drag coefficients. It means that the hydrofoil data obtained thanks to the 2D calculation on Xfoil is not right. Or at least, it cannot be used for a 3D calculation.
To check if this truly is the source of the problem, we chose to put directly the Fluent Cd and CL data as the input file of WT Perf. We obviously expect then to have a perfect match for the Cl and Cd values at least for the common values of AoA. We also expect the power to be closer from Fluent's.

2) Improvement of WT Perf calculation

For one given TSR value, the data (AoA, Cl, Cd) from Fluent simulation at this TSR is copied and pasted into the Xfoil data file. The Xfoil data is replaced by Fluent's data.

This replacement is repeated for each TSR value that we want to test.

TSR	Power SRF – Spalart Allmaras (kW)	Power WT Perf corrected (kW)	Error (%)
6	54	107	40
5.5	279	344	24
5.3	331	373	13
5	416	454	9
4.6	567	575	1.4
4.3	731	749	2.4
4	908	894	1.5

Figure 15: Fluent's and corrected WT Perf's power comparison

This is an effective improvement of the results: the difference (error%) between Fluent and WT Perf has noticeably decreased. But it remains high and is decreasing with the TSR.

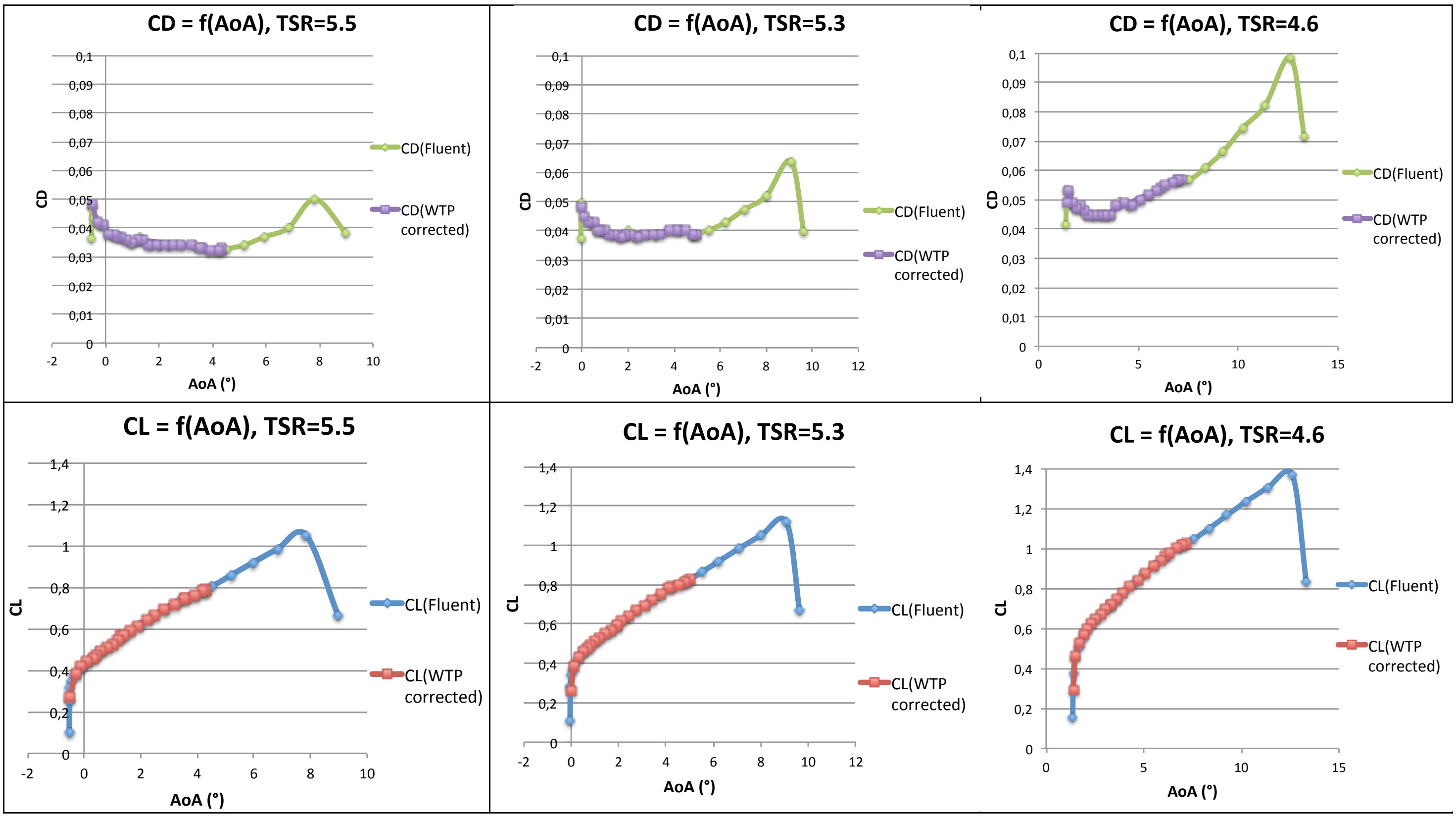


Figure 16: Cd and CL distributions for different TSR

The Cl and Cd are now matching, as expected.

The surplus of power for WT Perf method compared to Fluent's results is due to higher WT Perf Cl values on the region of the blade located between the middle and the tip (figuren°17). This part of the blade is very important for the power generation because its high distances from the hub enables a good torque.

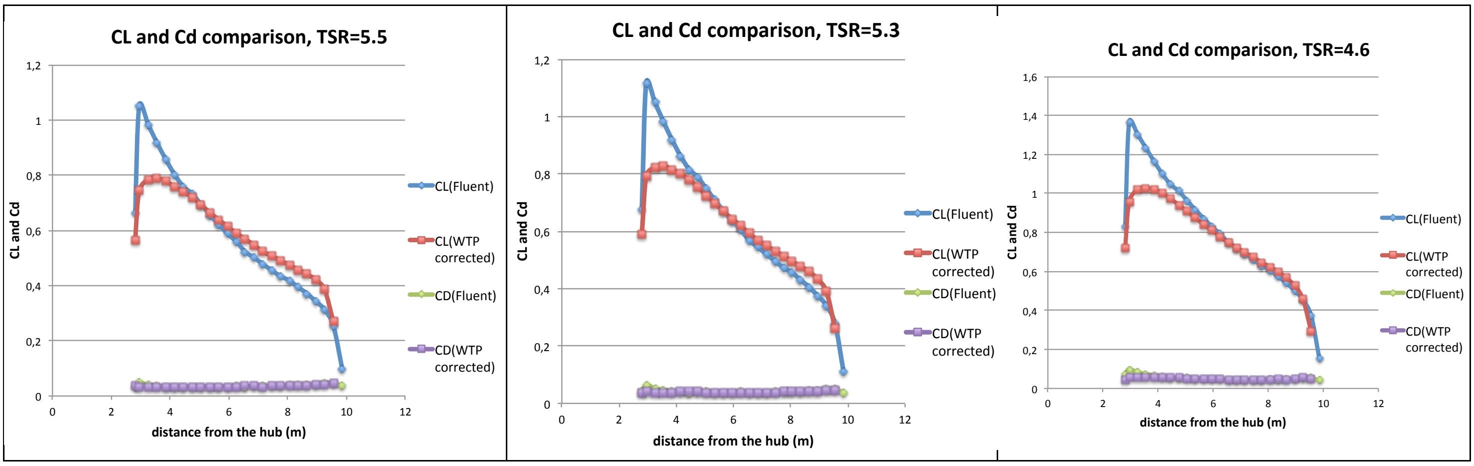


Figure 17: CL and Cd distributions for Fluent and corrected WT Perf

This difference of CL values is decreasing with the TSR. This is because the AoA's difference also tends to decrease with the TSR (figure n°15):

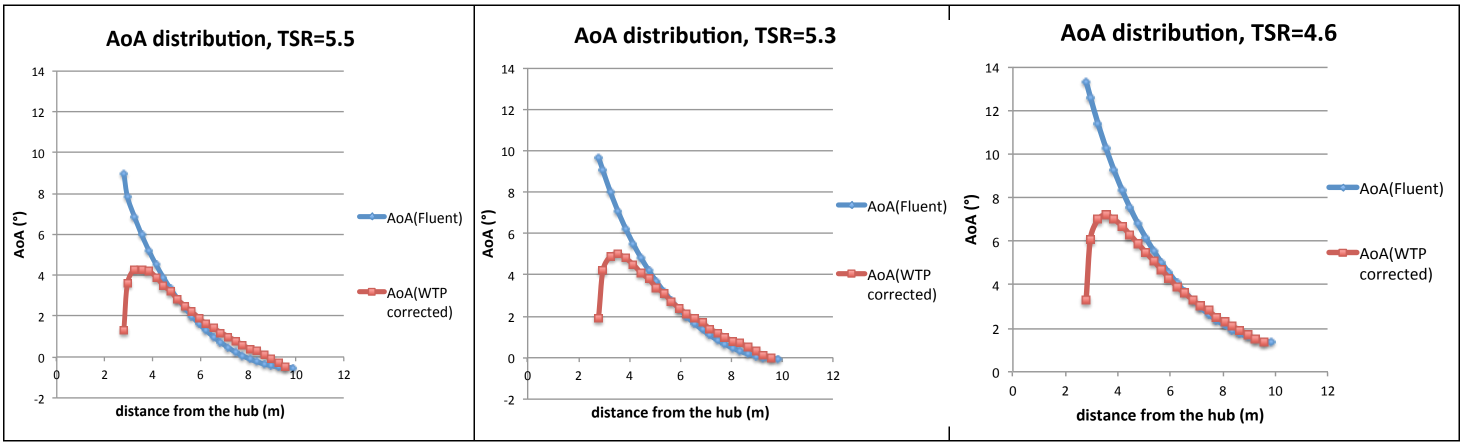


Figure 18: distributions of AoA

No we know that the power difference is due to an over-estimation of the AoA by WT-Perf in the 2nd half of the blade. This overestimation is increasing with the TSR, so it means that WT-Perf not capturing well th 3D effects for high TSR values.
The conclusion is that WT Perf is trustworthy only for low TSR values.

IV – New optimized operating conditions for the DOE model

1) New optimized operating conditions for Blade Pitch = 7°

As we noticed that the efficiency was still increasing when decreasing the TSR, we decided to go further by testing lower values until TSR=3.
All the performances are summed up in the following table:

TSR	Power SRF – Spalart Allmaras (kW)	Efficiency
6	54	0,1325
5.5	279	0,1763
5.3	331	0,1882
5	416	0,2028
4.6	567	0,2173
4.3	731	0,2244
4	908	0,2265
3.7	1143	0,2244
3.5	1330	0,2202
3	1899	0,1999

Figure 19: Power and efficiency for Fluent

Now if we plot the efficiency against the TSR values:

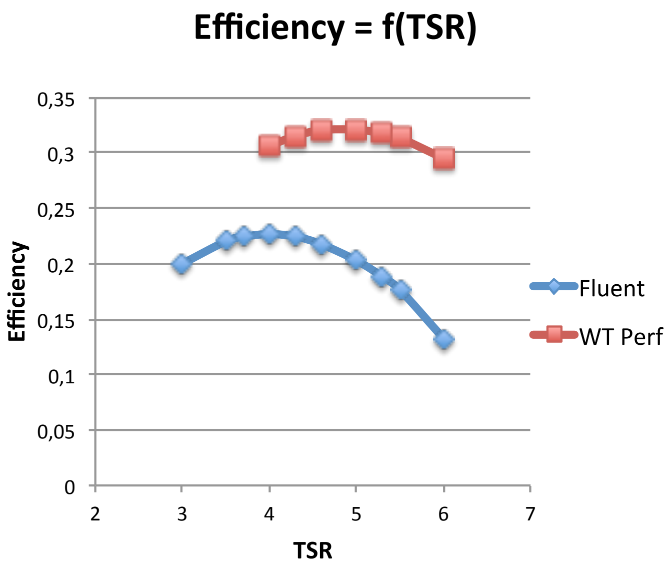


Figure 20: Efficiency for different TSR values

The efficiency peak is reached for TSR = 4 for Fluent.
We deduce that, eventually, the optimized conditions for a 7° blade pitch is a TSR = 4 instead of 5.3.

2) Optimized operating conditions for Blade Pitch = 0°

The data for TSR=7, 6.7 and 6.3 were previously simulated (see M.Tessier&N.Tomasini report).

TSR	Power SRF – Spalart Allmaras (kW)	Efficiency
7	245	0,2473
6.7	280	0,3321
6.3	342	0,3449
6	404	0,3406
5.5	551	0,3489
5	698	0,3403

V – Conclusions and leads for future work

Based on the work previously done by Mr. Teymour Javaherchi, A.Cerisola and M.Tessier and N.Tomasini, the study of the DOE Reference Model has been carried on.
A blade with a 7° pitch angle has been created from the 0° pitch angle blade, and then tested on Fluent for different flow conditions, with a SRF simulation.

The goal was to compare these results with the optimization table results, obtained with WT Perf.

It was deduced from this study that the XFOIL data giving the Cd,CL and Cp tables weren't giving good results. This is because XFOIL is doing a 2D flow simulation whereas our case is a 3D flow. We chose to improve the WT Perf simulation accuracy by directly putting Fluent's CL,Cd data (for ONE given value of TSR) as the input files for WT Perf. This resulted in a much better agreement between Fluent and WT Perf's results. The power got with WT Perf is getting closer to Fluent's power when decreasing the TSR. It means that WT Perf is not capturing well the 3D effects.

As looking at the performances, we noticed that the performances of the turbine were improving when going toward lower values of TSR. By testing a range of values going from 6 to 3, we deduced that the optimized operating condition for a 7° blade pitch was a TSR=4 instead of TSR=5.3.

As the 0° blade pitch geometry was also available (previously studied by M.Tessier&N.Tomasini) we decided to extend the range of tested TSR values. The optimization table says that we should start increasing the pitch (from 0° value) as soon as we get a TSR<6.3.

As for the 7° blade pitch case, we deduce here that this limit TSR value can be decreased until ?????

In a general observation, we see that the optimization table is over-estimating the pitch for each flow conditions.

This is a lead for future studies: other pitch angle studies should be done to complete the "new" optimization table, obtained thanks to Fluent's results.

The study was performed with SRF numerical method and the Spalart-Allmaras turbulence model. It is of course possible to test the k-w turbulence model.

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