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HYDRODYNAMIC PERFORMANCE OF A BIOMIMETICALLY IMPROVED TIDAL TURBINE BLADE

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This paper contributes into the investigations on the feasibility of improving the performance of a marine current turbine using a biomimetic concept inspired from the leading edge tubercles at the flippers of humpback whales. An experimental test campaign has been recently conducted in the Emerson Cavitation Tunnel at Newcastle University and some details of this test campaign together with the findings are summarised in the paper.

A set of tidal turbines with different leading-edge profiles was manufactured and tested to evaluate the effect on the hydrodynamic performance. Various tests, which included performance, flow observations, noise and cavitation, were conducted under different speed and different pitch angle settings of the turbine blades. Eventually, by these investigations, the advantage and disadvantage of applying the leading-edge tubercles on the hydrodynamic performance of the tidal turbines were evaluated as well as further understanding of this biomimetic concept in applying on to tidal turbines.

As far as the performance tests are concerned, the results showed that the models with the leading-edge tubercles had a better performance in the lower tip speed ratios (TSRs) and at lower pitch angle settings where the turbine blades were working under the stall conditions. Furthermore, the tubercles have enabled to start the turbines quicker at very low TSR range. In the meanwhile the biomimetic concept did not compromise the maximum power coefficient value of the turbine without the tubercles but shifted the distribution of the coefficient over the range of the tip speed ratios tested.

1. Introduction

With the depletion of the traditional fossil energy, protection of energy reserves has been high on the agenda of many governments. Massive investment has been granted in renewable energy field to exploit the sustainable energy resources. Tidal energy is one of the sustainable energy resources resulting from gravitation effects of the planets and the moon, which has become a very attractive option as it is resourceful and highly predictable [1, 2]. However the development of this technology is highly depended on the local current speeds and most areas around the world have rather moderate current speed ranging from 1 to 2 m/s. To explore tidal energy in such area needs some improvement in the design of tidal energy devices to adapt to the local condition to extract best of this energy.

Recently the tubercles on the leading edges of the humpback whale flippers have drawn the attention of the researchers working in the field of tidal energy and wind energy, as these round protuberances along the leading edges indicate to have the ability to delay the stall and improve the lift-to-drag ratio [3-8]. Many research studies, which are both in numerical and experimental nature,

have investigated the influence of the leading-edge tubercles as applied on air fans, wind turbines, rudders and so on [8-12]. According to these studies, blades with the leading edge tubercles can maintain lift coefficients further beyond the stall point in comparison to those without the tubercles.

Taking advantage of these applications and to improve the tidal turbines' performance, recently an attempt to apply the tubercles on a tidal turbine blade was conducted and performance comparisons of tidal turbine models with different tubercle designs were carried out in a towing tank[13]. Even though certain performance improvement was shown in this test campaign, because the power coefficients were rather low compared with the other tidal turbines this finding has been questioned on the ground whether the performance improvement was due to the effect of the leading-edge tubercles or it was accidental. Therefore there was a scope for further research to explore and validate this biomimetic concept via other turbine applications where the turbine models had better performances.

Within the above framework, this paper investigates the hydrodynamic performance of tidal turbines with and without the leading-edge tubercles. A preliminary hydrofoil study was conducted to study the effect of the leading edge tubercles as applied on a "straightened" turbine blade which was based on a tidal turbine designed and tested in the Emerson cavitation tunnel (ECT), Newcastle University [14]. With the knowledge gained from this earlier hydrofoil study three tidal turbines with different leading-edge profiles have been designed and tested in the ECT. In the remaining part of the paper the details of the turbine design and models, performance tests and results from the tests are presented and discussed to demonstrate the effect of the leading edge tubercles mainly on the torque, thrust, efficiency and cavitation performance.

2. Design and manufacture of turbine models

A horizontal axis tidal turbine (HATT) is chosen to be the reference turbine to apply the leading-edge tubercles on. This turbine model was designed and tested during a previous project [15] and validated by a CFD study [16]. The main parameters for the blades of this 400mm diameter model turbine are shown in Table 1.

Table 1 - Main particulars of the tidal stream turbine model

r/R	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
Chord length(mm)	64.35	60.06	55.76	51.47	47.18	42.88	38.59	34.29	30
Pitch angle (deg)	27	15	7.5	4	2	0.5	-0.4	-1.3	-2

The profile design of the leading-edge tubercles was optimised and validated by a preliminary study. In the study a "straightened" tidal turbine blade, which was designed based on this tidal turbine blade but straightened with a constant pitch angle, was used and tested for validations as shown in Fig. 1 (left) [14]. The amplitude of the tubercles was equal to 0.1C while the wavelength was 0.5C with C is being the chord length of the foil. Thus approximately 8 sinusoidal tubercles could be evenly distributed along the leading edge of the foil. From this preliminary optimisation study it was found that the hydrofoil with 8 leading-edge tubercles (assigned as: Sin_8), had a better hydrodynamic performance than the one without the tubercles (assigned as: Ref), under the stall condition as shown in Fig. 1 (right).

Based on the optimisation and validation study, three pitch adjustable turbine models with different leading-edge profiles were manufactured as shown Fig. 2. The turbine model without tubercles is

named as “Ref”; while the one with two leading-edge tubercles at the tip is named as “Sin_2”; at the same time the one with eight leading-edge tubercles is named as “Sin_8”.

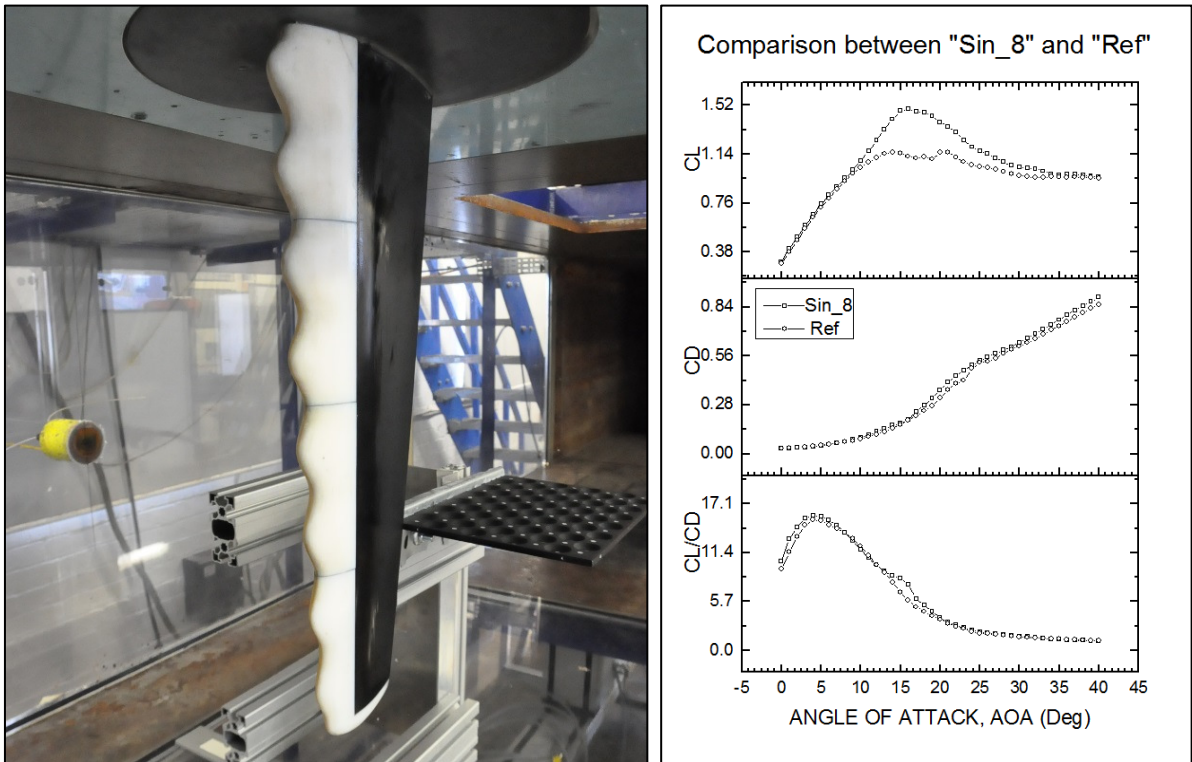


Fig. 1 - Hydrofoil study for tubercle design and optimization [14] (Left: the tested hydrofoil model; Right: the tested result)



Fig. 2 - Tested turbine models

3. Experimental set-up and model tests

The three tidal turbine models were manufactured by CTO, Gdansk and tested in the Emerson Cavitation Tunnel at Newcastle University. The sketch of the tunnel is shown in Fig. 3. The tunnel is a medium size propeller cavitation tunnel with a measuring section of 1219mm×806mm (width × height). The speed of the tunnel water varies between 0.5 to 8 m/s. Full details of the ECT can be found in [17].

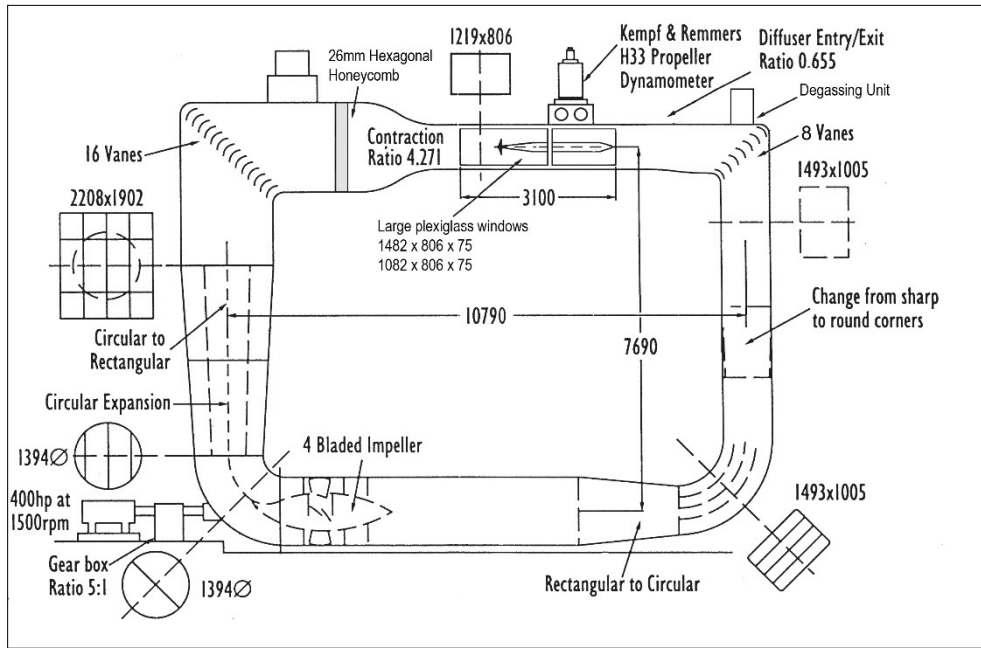


Fig. 3 - Sketch of Emerson Cavitation Tunnel

The turbine was mounted on a vertically driven dynamometer K&R H33 to measure the thrust and torque of a propeller or turbine. The main technical data of H33 are given in Table 2. On top of the dynamometer, a three-phase DC motor (64kW at 415 V) is mounted to control the rotational speed of a turbine.

Table 2 - Technical data of propeller dynamometer K&R H33

Type of dynamometer	Kempf & Rammers H33
Rated maximum thrust (N)	±3000
Rated maximum torque (Nm)	±150
Maximum rotation speed (RPM)	4000

During the model test the torque and thrust of the turbine were measured, from which the power coefficient and the thrust coefficient can be derived by using the following equations:

$$C_p = \frac{Q\omega}{\frac{1}{2}\rho A_T V^3} \quad (1)$$

$$C_T = \frac{T}{\frac{1}{2}\rho A_T V^2} \quad (2)$$

where Q is the torque of the turbine, Nm; T is the thrust, N; ω is the rotational speed, rad/s; A_T is the swept area of the turbine and equals to $\pi D^2/4$, m²; ρ is the tunnel water density, kg/m³; V is the incoming velocity, m/s, D is the turbine diameter, m.

The rotational speed is controlled by the motor to achieve the desired tip speed ratio (TSR) which can be calculated by Equation 3. As the performance of the turbine is strongly depended on the Reynolds number, $Re_{0.7r}$ and cavitation number, $Cav_{0.7r}$ these two non-dimensional quantities, were monitored during the tests and described in Equation 4 and 5 based on the resultant velocity at 0.7 blade radius, r , respectively.

$$TSR = \frac{\omega r}{V} \quad (3)$$

$$Re_{0.7r} = \frac{C_{0.7r} \sqrt{(V^2 + (0.7\omega r)^2)}}{\nu} \quad (4)$$

$$Cav_{0.7r} = \frac{P_{0.7r} - P_v}{\frac{1}{2} \rho \sqrt{(V^2 + (0.7\omega r)^2)}} \quad (5)$$

where $C_{0.7r}$ is the chord length of the turbine at 0.7 radius, m; ν is the kinematic viscosity of the water, m^2/s ; $P_{0.7r}$ is the static pressure at the upper 0.7 radius of the turbine, Pa; P_v is the vapour pressure of the water, Pa.

During the tests, the incoming velocity of the tunnel was fixed and the rotational speed was varied to achieve certain TSR required. The tests were conducted according to the test matrix shown in Table 3 and each run repeated for three times. The test conditions were also shown in graphical format at Fig. 4. At high Reynolds numbers, due to the increased incoming velocity, cavitation number are reduced and hence cavitation might be occurred at the turbine blades. Taking the advantage of the pitch adjustable design, three different pitch angles of the turbine blades were tested.

Table 3 - Test matrix

V	TSR	RPM	Pitch angle	Tunnel pressure	Cav	Re
(m/s)			(°)	(mmhg)	(0.7r)	(0.7r)
2	0.5 ~ 8	47 ~ 763	0	850	48.534 ~ 1.684	0.76E+05 ~ 2.24E+05
2	0.5 ~ 8	47 ~ 763	+4	850	48.534 ~ 1.684	0.76E+05 ~ 2.24E+05
2	0.5 ~ 8	47 ~ 763	+8	850	48.534 ~ 1.684	0.76E+05 ~ 2.24E+05
3	0.5 ~ 8	71 ~ 1145	0	850	21.571 ~ 0.748	1.15E+05 ~ 3.36E+05
3	0.5 ~ 8	71 ~ 1145	+4	850	21.571 ~ 0.748	1.15E+05 ~ 3.36E+05
3	0.5 ~ 8	71 ~ 1145	+8	850	21.571 ~ 0.748	1.15E+05 ~ 3.36E+05
4	0.5 ~ 8	95 ~ 1527	0	850	12.134 ~ 0.421	1.53E+05 ~ 4.48E+05
4	0.5 ~ 8	95 ~ 1527	+4	850	12.134 ~ 0.421	1.53E+05 ~ 4.48E+05
4	0.5 ~ 8	95 ~ 1527	+8	850	12.134 ~ 0.421	1.53E+05 ~ 4.48E+05

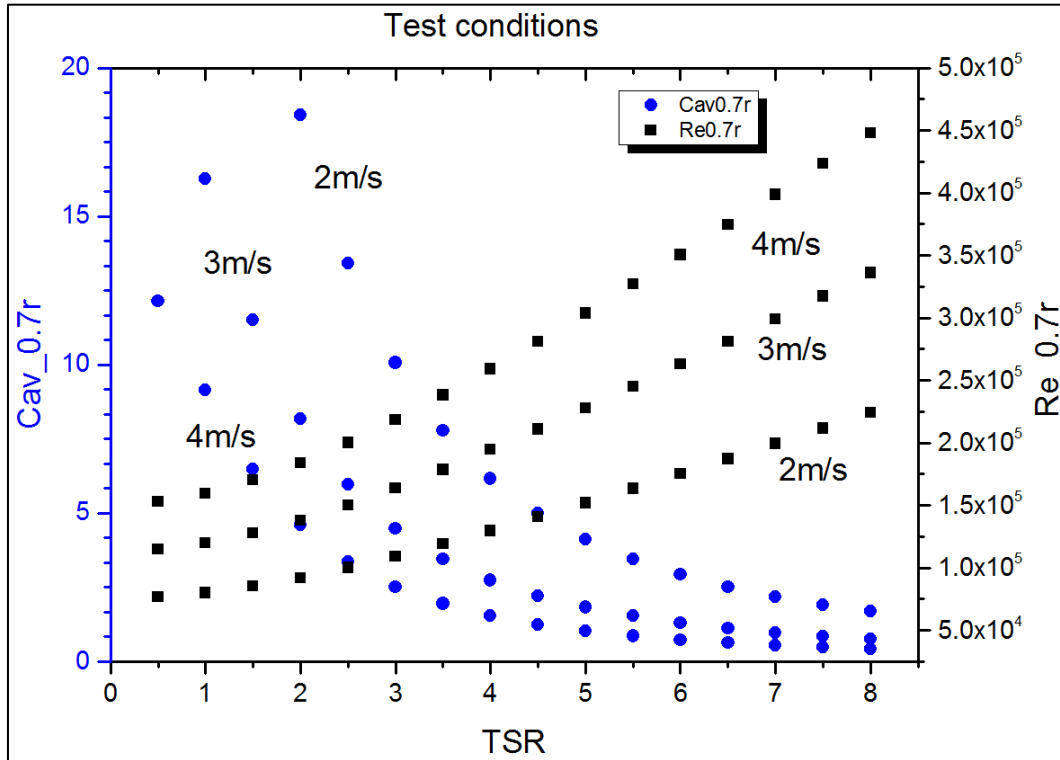


Fig. 4 - Test conditions

4. Test results and discussions

In order to analyse the effect of the leading-edge tubercles, independently, each turbine model was tested by using the test matrix shown in Table 3. And then the turbine performances were compared based on the same condition for the reference turbine and other two turbines with the tubercles. All the cases were coded as “Model Name_Pitch Angle_Test Velocity” and, for example “Ref_0_2” indicated the test results for the reference turbine model with 0° pitch angle setting tested at 2m/s incoming velocity.

4.1. Effect of Reynolds number and blade cavitation

As shown in the Table 3 and Fig. 4, the Reynolds number and cavitation number are cross related to each other at the constant tunnel pressure and determined by the incoming velocity and TSRs. In order to study the influence of the Reynolds number and the cavitation number, the reference turbine model with the smooth leading edge, “Ref”, was first tested under different incoming velocities, i.e. 2, 3 and 4 m/s while the blade pitch angle was set to 0°.

Based on the test results the power coefficients, C_p , and thrust coefficients, $C_t/10$ were calculated and presented in Fig. 5. In this figure the C_p curves marked by the red colour are the data where cavitation inception occurred. The test results indicated that while the C_p curve would be greatly influenced by the blade cavitation, increasing the Reynolds number would only lead to a slight enhancement in the performance. However this was also based on the types of cavitation developed.

During the tests various types of cavitation were observed including tip vortex cavitation, cloud cavitation at the back side and face side of the blade, as shown in Fig. 6, depends on the TSR. The development sequence of these cavitation types on the blades was as such usually the tip vortex

cavitation was first appeared and then gradually transformed to a more severe and unsteady cloud cavitation on either side of the turbine blade depends on the TSR. While the cloud cavitation would greatly reduce the turbine efficiency it could also cause erosion on the blades.

Based on the test results it was noticed that Reynolds number and tip vortex cavitation had a limited influence on the turbine performance in comparison to the effect of the cloud cavitation which would not only cause efficiency loss but also expected erosion damage on the blades. It is therefore important to compare the turbine performance not only based on the same TSR but also based on the same Reynolds number as well as the cavitation number.

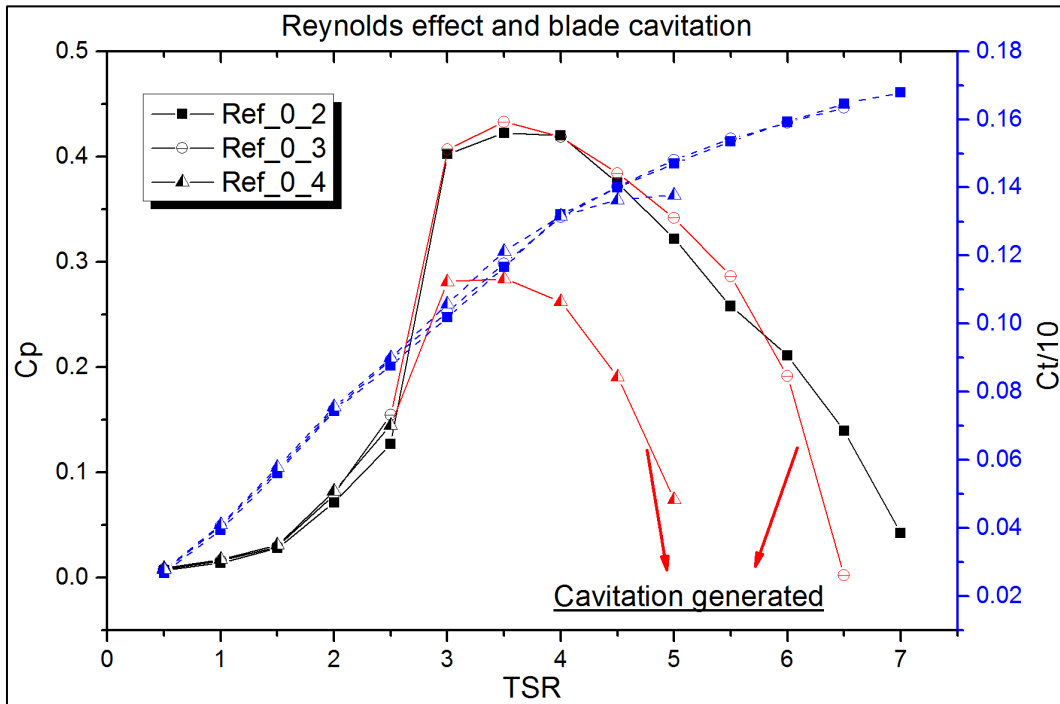


Fig. 5 - Influence on turbine performance caused by Reynolds number effect and blade cavitation

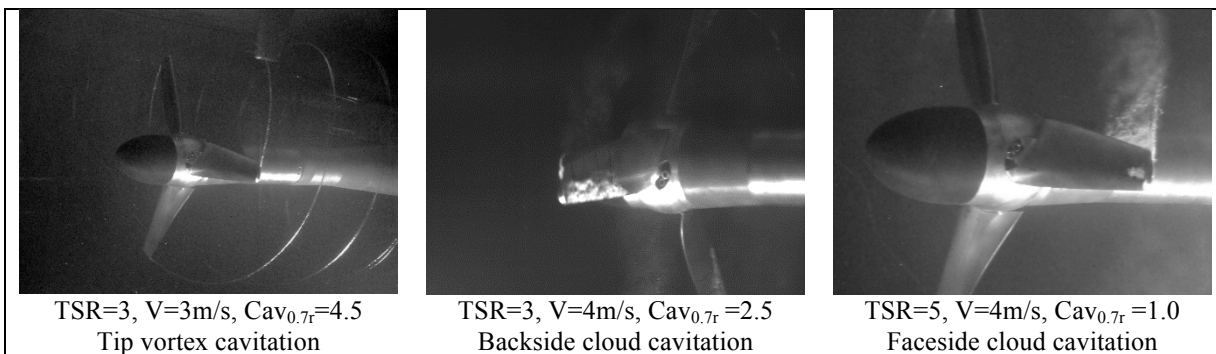


Fig. 6 - Types of blade cavitation

4.2. Effect of blade pitch angle

Another important factor that influences the turbine performance is the blade pitch angle. During the tests three different pitch angles, 0° , $+4^\circ$ and $+8^\circ$ were imposed on the turbine blades. From the test results of the reference turbine, as shown in Fig. 7, the $C_t/10$ was significantly reduced by increasing pitch angle. On the other hand the C_p reached at its maximum value (0.49), with $+4^\circ$ pitch angle, while $+8^\circ$ pitch angle provided the turbine with a better performance over the lower range of TSRs until $TSR=2.5$.

Based on the test results the reference turbine had the best efficiency over the widest TSR when the blade pitch angle was set to $+4^\circ$. When the blade pitch angle was set to 0° the force on the blade contributed more in the thrust, while for the case $+8^\circ$ the increased pitch angle resulted in a reduced angle of attack and hence lower thrust force on the turbine.

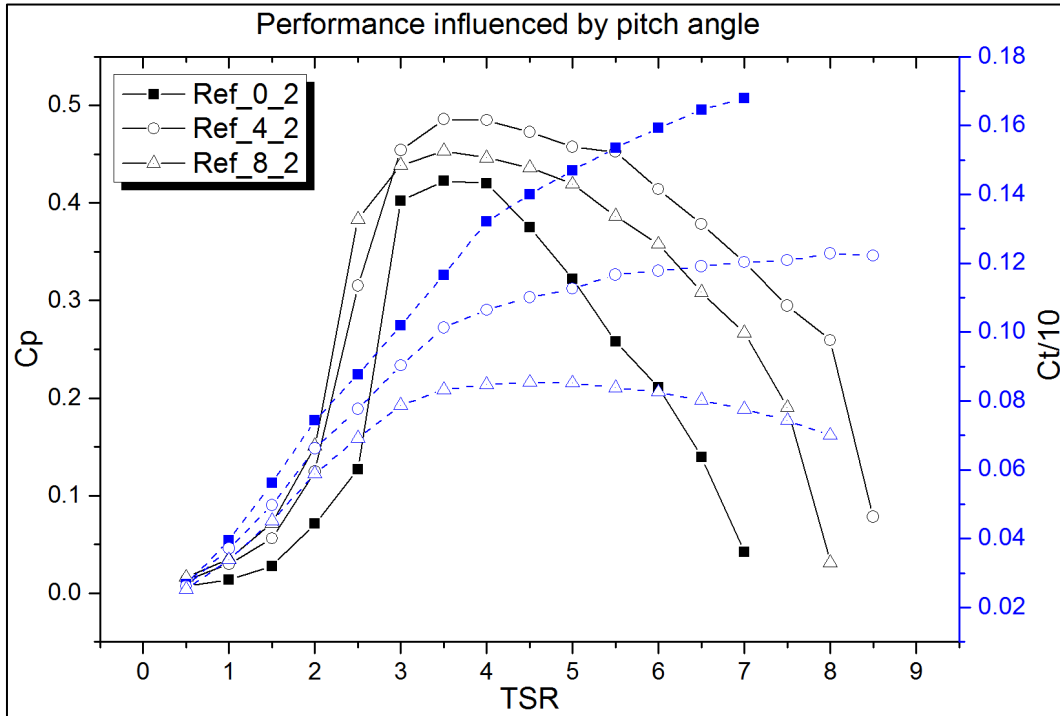


Fig. 7 - Performance influenced by pitch angle

4.3. Effect of different leading-edge tubercle profiles

Following the tests with the reference turbine, the two counterpart turbines with the different leading-edge profiles were tested using the test matrix given in Table 3 but at a constant incoming velocity of 2 m/s. The reason for selecting 2 m/s of incoming velocity was due to the negligible effect of the Reynolds number on the turbine efficiency as opposed to the considerable effect of the cavitation as discussed in Section 4.1 and 4.2. Therefore in order to investigate the effect of leading edge tubercles on the blade performance independent from the cavitation and blade pitch angle, the result of the tests at 2m/s was used for comparisons with the results of the reference turbine. Each set of tests was repeated for three times and averaged to achieve the final result.

First all the turbine models with 0° pitch angle were tested and the results are presented in Fig. 8. It can be noticed that the leading-edge tubercles can improve the performance of the turbine in the lower end of TSRs, where the turbine is suffering from stall. Turbine can generate more force, which can be observed in both C_p and $C_t/10$. However with the increase in TSR, the C_p values of the Ref turbine and Sin_2 turbine firstly reaches at the maximum value of 0.43, at TSR=3.5, while the turbine Sin_8 reaches its maximum with a little delay at TSR=4. On the higher end of TSRs turbine Sin_2 and Sin_8 generate more torque and less thrust.

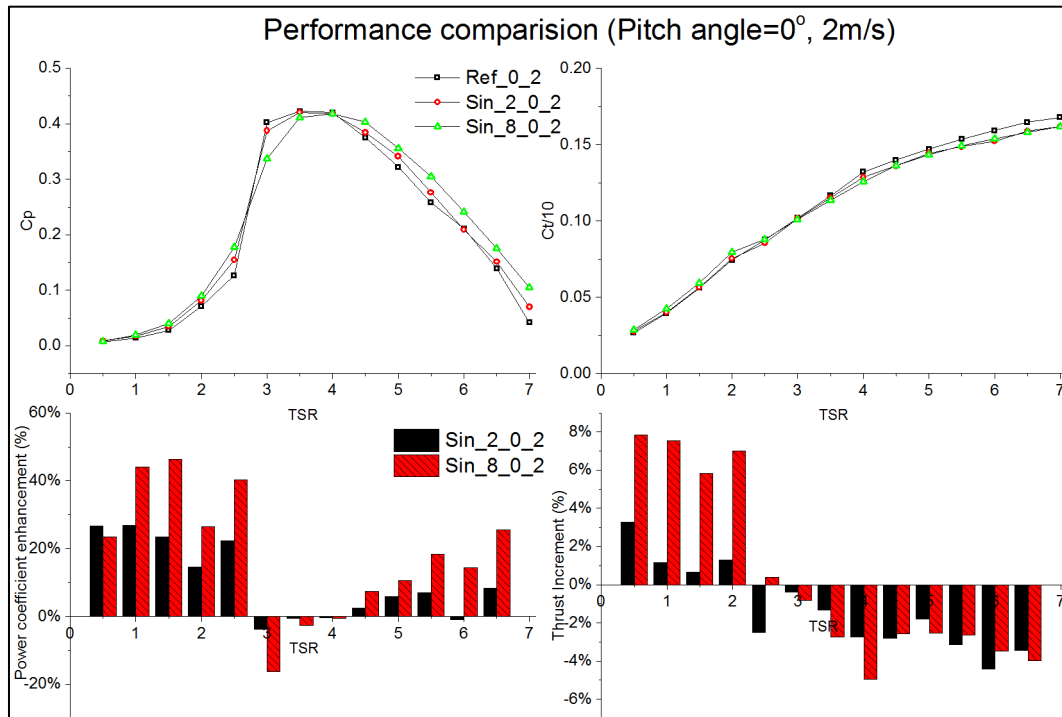


Fig. 8 - Performance comparison (Pitch= 0° , 2m/s)

Following the 0° pitch angle tests the pitch angle setting was increased to $+4^\circ$, which was the most efficient pitch setting for the reference turbine, and tests were repeated. As shown in Fig. 9, similar to the results with the 0° pitch angle, the leading-edge tubercles can contribute more in torque at the lower end of the TSR range as well as in thrust. Compared with Sin_2, the impact caused by Sin_8 is more obvious in both C_p and $C_t/10$. On the other hand the effect of the leading-edge tubercles was smaller relative to that in 0° pitch angle. As noticed the leading-edge tubercles did not have any effect on the maximum C_p apart from shifting its TSR from 3.5 to 4.0.

Following the same procedure, the turbine models with 8° pitch angle were tested and results were evaluated. According to the Fig. 10, as expected and in-line with the results of the previous test cases, the tubercles improved the performance over the lower TSR range and did not have any obvious impact on the maximum C_p . However, the leading edge tubercles significantly increased the thrust coefficient, $C_t/10$, around 10% increment caused by Sin_8. This indicated that the blades are generating higher force however this force contributes more to the thrust than the torque.

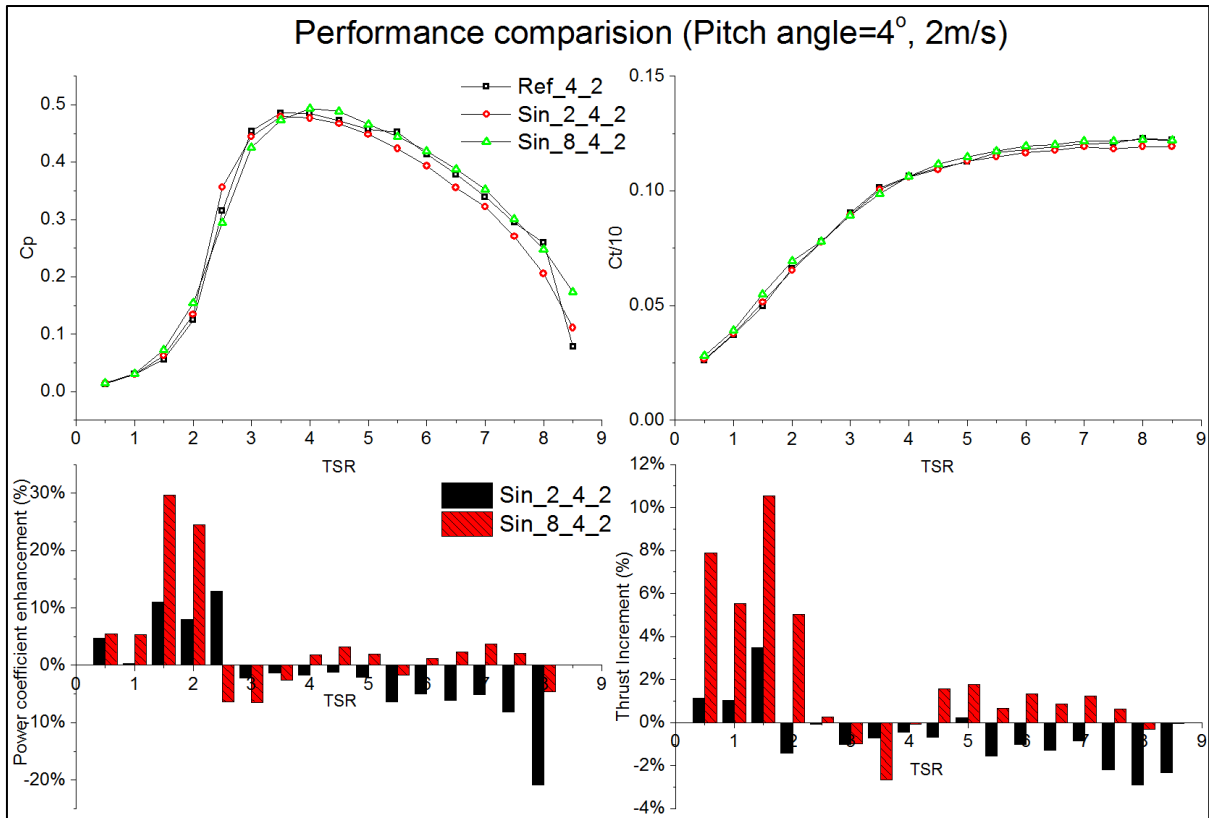


Fig. 9 - Performance comparison (Pitch=4°, 2m/s)

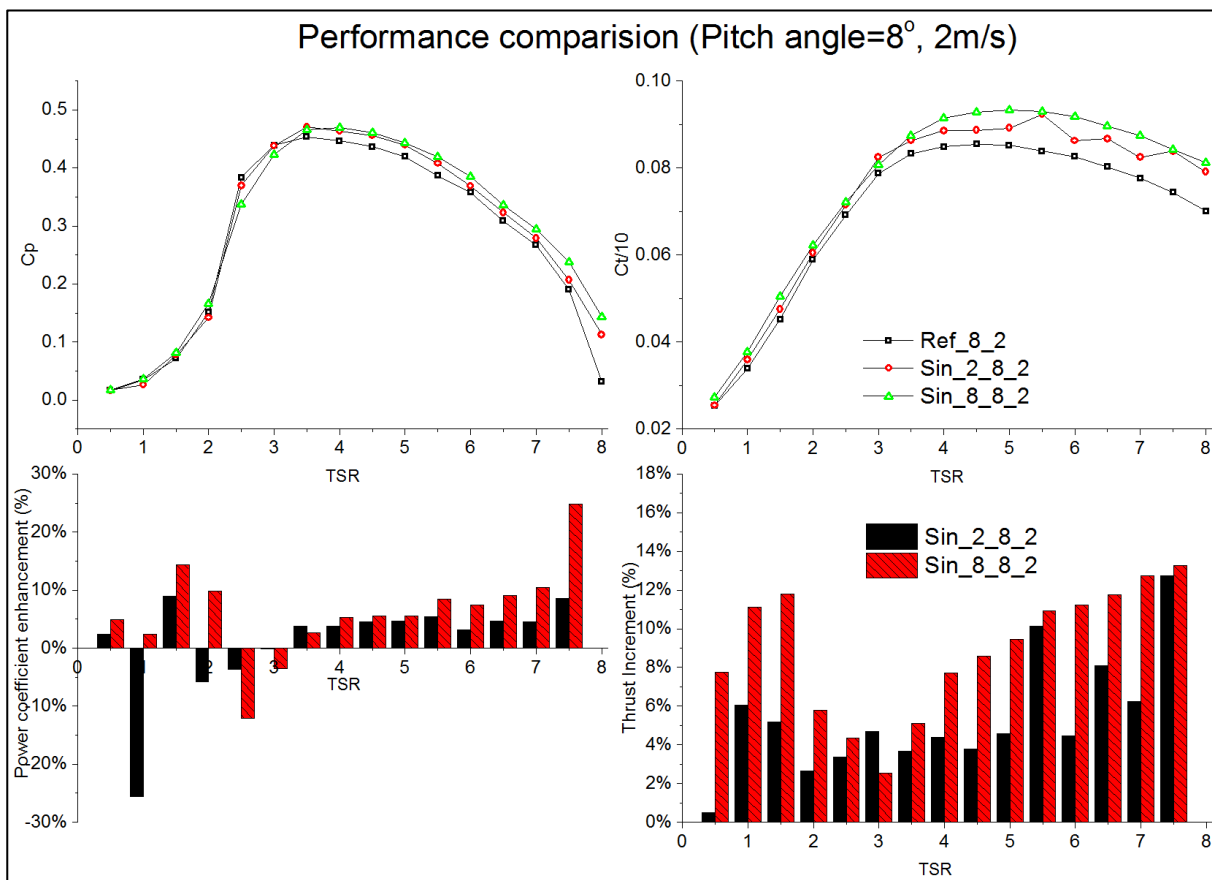


Fig. 10 - Performance comparison (Pitch=8°, 2m/s)

5. Conclusions

A group of tidal turbine models with and without the leading tubercles on their blades have been tested in the Emerson Cavitation Tunnel for further understanding of their effects on the hydrodynamic performance of the turbines. According to the test result, the following conclusions can be drawn:

1. The impact of the leading-edge tubercles is mainly on the lower range of TSRs, while the blade is operating under stall conditions. Leading-edge tubercles can greatly enhance the force generated by the turbine blade, which can both result in a higher torque and also a higher thrust.
2. For the lower pitch angles, the improvement caused by the leading-edge tubercles is higher than the one for the higher pitch angle. It is also proved that this biomimetic concept can help to improve the performance while the turbine is working under stall conditions. Turbine with the leading edge tubercles will start earlier in a current.
3. The application of the leading edge tubercle concept does not compromise the maximum power coefficient value of the turbine but slightly shifts the distribution of this coefficient over the tip speed ratios tested, towards the higher range.

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