Performance prediction of a horizontal axis marine current turbine by experimental and numerical studies

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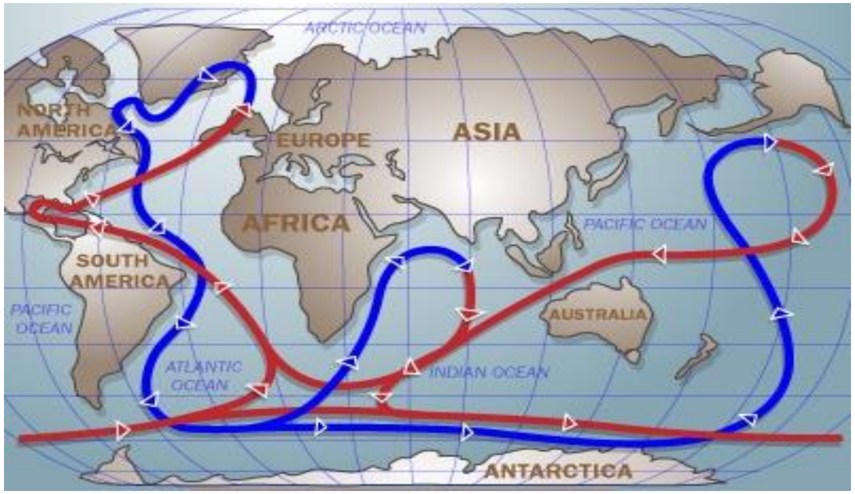
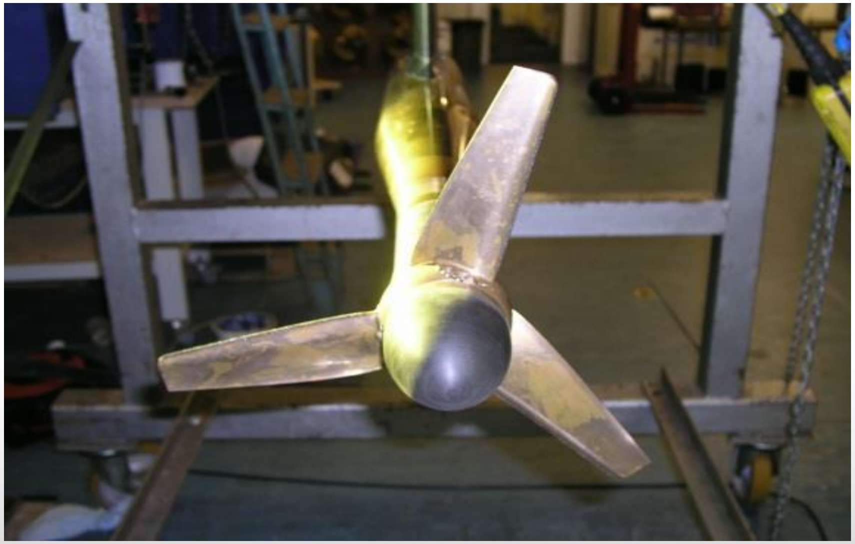
Introduction and Scope

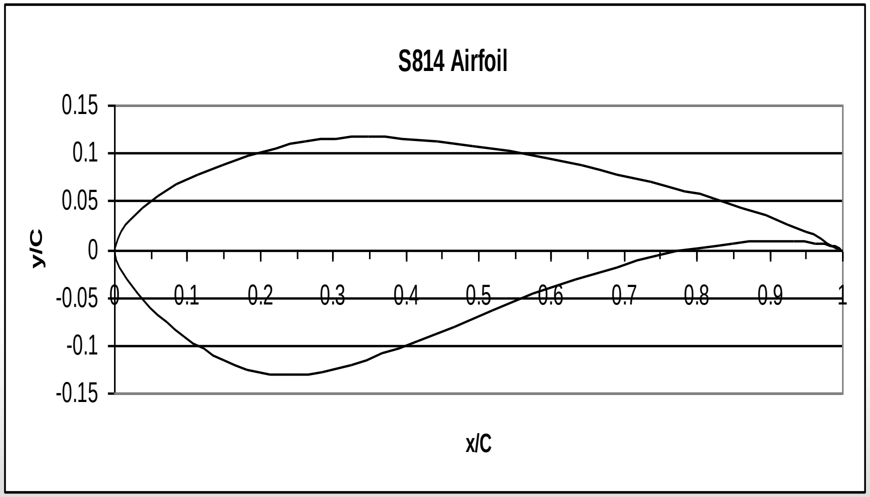
- The large potential possessed by marine currents is regarded as a predictable and sustainable resource for wide scale generation of electrical power.
- To exploit this potential efficiently, experimental and numerical studies have always been crucially important for design and validation practices for marine current turbine applications.
- This presentation mainly includes the results of cavitation tunnel tests on a 400mm diameter model of a marine current turbine.
- Results acquired for cavitation observations for three different cavitation conditions as well as power and thrust coefficients for a range of tip speed ratios are presented.
- The aim of power extraction performance tests was to obtain the efficiency of the rotor to extract energy from tidal stream currents in a range of tip speed ratios.





Model experiments -A Brief Description of the Model Turbine

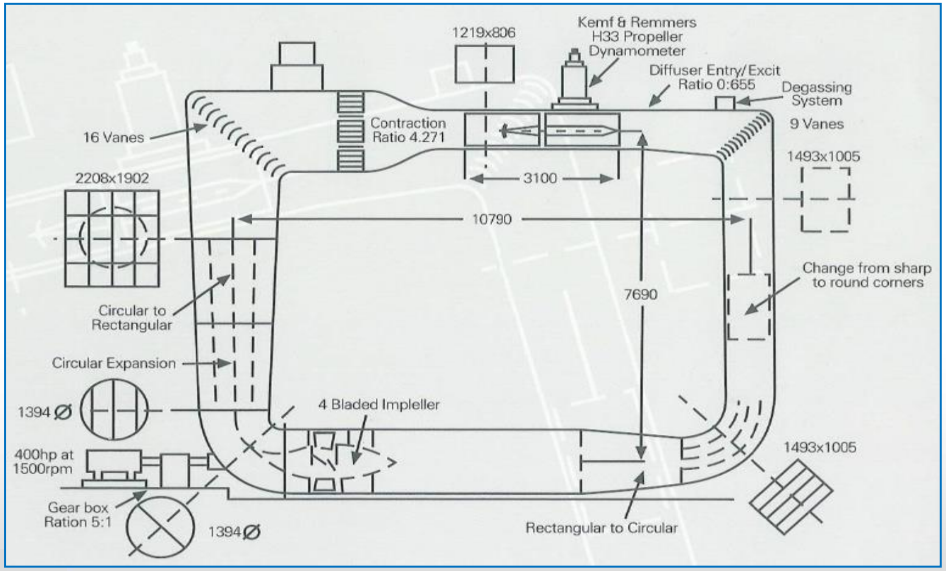
- The tested stream turbine was a three-bladed and [1]stall-regulated turbine designed to operate in a tidal stream speed of 3.5 m/s with a shaft speed of 12 revolutions per minute and a diameter of 20 meters in full scale.
- The turbine was scaled (1/50) to a pitch-controllable model of 400 mm in diameter.
- The blade section S814, as shown in Figure, was adopted for the blade sections along radius.
- The turbine model was manufactured in such a way that pitch values of the blades can be set in a range of -50 to 150 degrees (design pitch angle is zero degrees at $R_{0.7}$).



[1]blades are designed and shaped to increasingly "stall" the blade's angle of attack with the wind to both maximize power output and protect the turbine from excessive wind speeds

Model experiments – Testing Facility

- The model tests of this turbine were carried out in NCL University - Emerson Cavitation Tunnel, having a test section of 1.26m x 0.8m and 3.1 m in length.
- The tested turbine was mounted on a vertically driven Kempf &Remmers type H33 dynamometer as shown in figure. This dynamometer was used to measure the thrust and torque of the model turbine.
- On top of the dynamometer, a motor was mounted to drive a propeller or to absorb the power generated by the turbine and control the rotation rate.



Model experiments - Definitions of Basic Parameters for a Rotor

- To test a model turbine at the same conditions as that of its full scale, the turbine model has to be tested at the same tip speed ratio calculated from the following equation,

$$Tip\ Speed\ Ratio = \frac{\Omega R}{U} = \frac{2\pi n R}{U * 60}$$

- Where U is tunnel water speed; R is the turbine radius, Ω is rotational speed (rad/s) and n is revolutions per minute (rpm) of the turbine model.
- Angle of attack or pressure distribution at each blade section of a turbine is considered to be the same between model and full scale turbine as long as they have the same tip speed ratios [9].
- During the experiment, tunnel water speed was maintained constant while rotational speed of the turbine model was controlled to vary in obtaining certain tip speed ratios.
- At each set of rotational speed, the torque and thrust of the turbine model were measured. Then power and thrust coefficients were calculated using equations below,

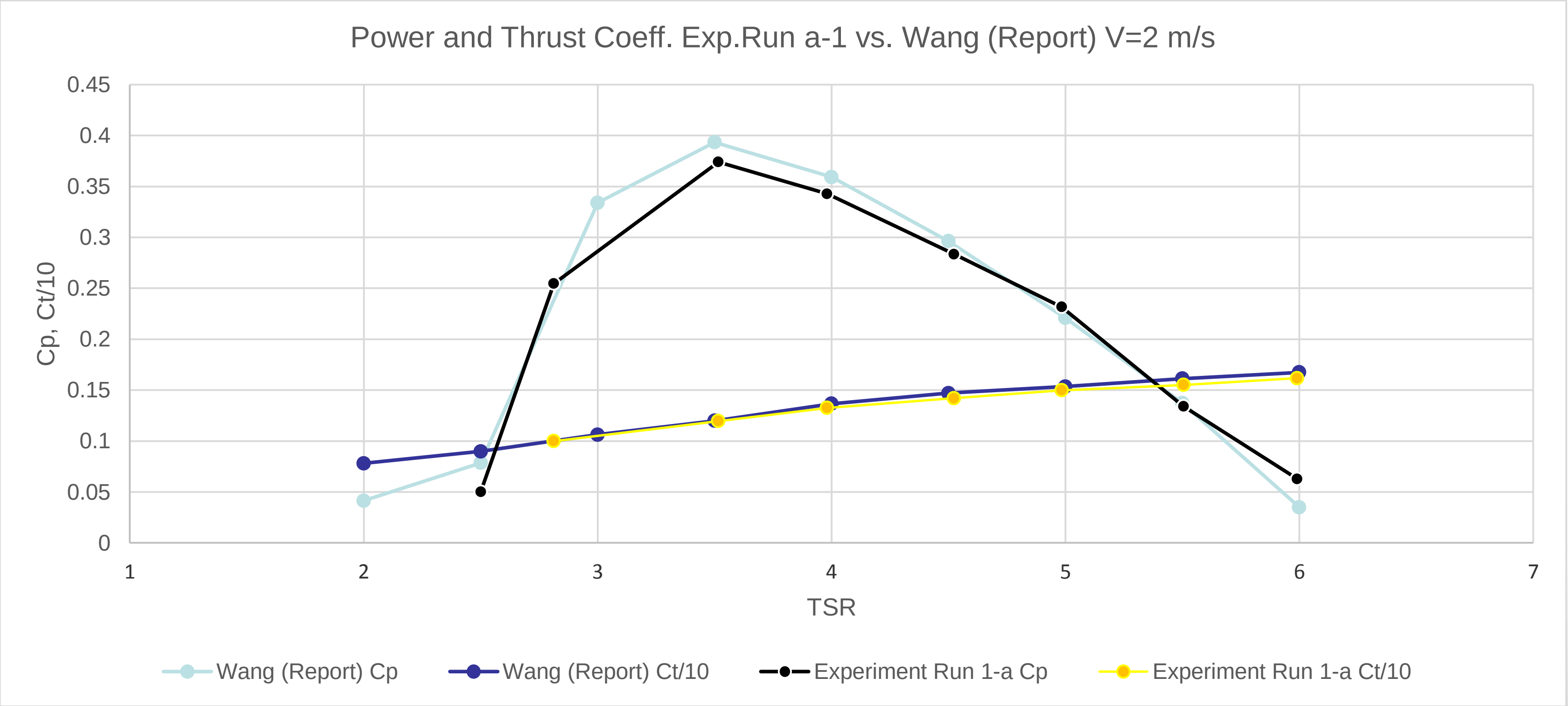
$$Power\ Coeff. = \frac{2\pi n Q}{0.5\rho\pi(D/2)^2 U^3} = \frac{16 n Q}{\rho D^2 U^3}$$

$$Thrust\ Coeff. = \frac{T}{0.5\rho\pi(D/2)^2 U^2} = \frac{8T}{\rho\pi D^2 U^2}$$

- Here, ρ is the density of water (kg/m^3), D is the diameter of the rotor, Q and T are the measured torque (Nm) and the thrust (N) of the turbine respectively.

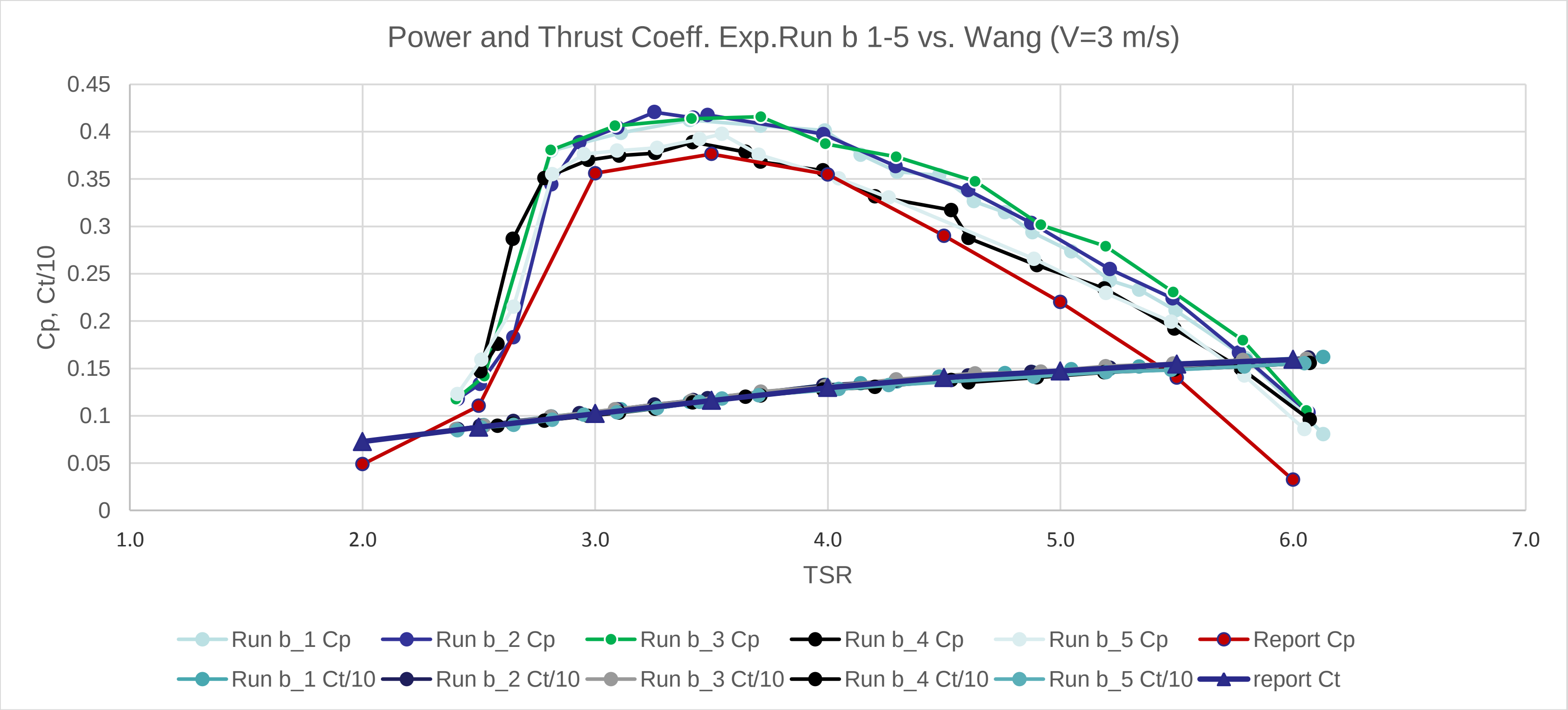
Model experiments – Experimental Results

- The torque and thrust of the rotor are measured in a range of tip speed ratios (by means of varying the rotation rate of the rotor) in which the rotor will extract energy from water. The tests were carried out once at 2 m/s of constant water speed and the results are shown in figure below. Compared to the results of the previous experimental study[9], slightly higer Cp values were measured.



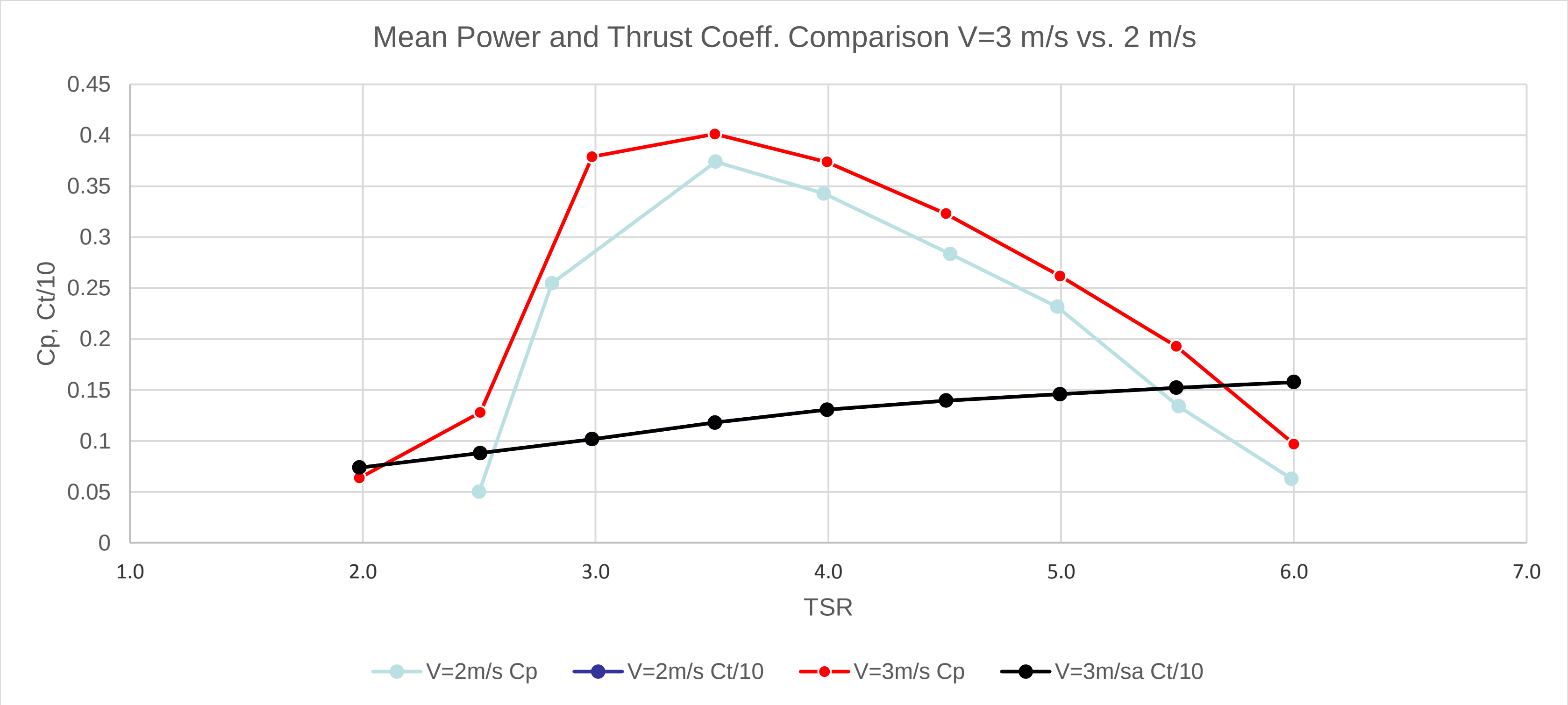
Model experiments – Experimental Results

- Tests were also conducted at 3 m/s of constant water speed for five times and during the repeated tests, it was seen that the test results were quite scattered and compared to the results of aforementioned experimental study, slightly higer Cp values are measured at each run. Results are shown in figure below.



Model experiments – Experimental Results

- Comparison of the power and thrust coefficients, tested with 2m/s and 3m/s water speed is shown in Figure. The power coefficients tested are very close to each other though slightly higher Cp values measured at 3m/s tunnel water velocity.



Model experiments - Cavitation Observation Tests

- The cavitation phenomenon occurs when the pressure at suction side of a turbine blade section becomes lower than the vapour pressure and can cause reduction in efficeincy, blade erosion, vibration and noise.
- In order to simulate cavitation, just like the tip speed ratio similarity, the model turbine has to be tested at the same cavitation number, which is a dimensionless coefficient, and defined as:

$$\sigma = \frac{P - P_v}{0.5\rho V_R^2}$$

- Where P is pressure of the interested point (0.7R in this case); P_v is the vapour pressure of the water; ρ is the density of water and V_R is the velocity at the reference point.

- In order to reduce the scale effect on cavitation, the air content dissolved in the water has to be maintained at the required levels. During experiments the gas content is calculated using the expression below:

$$\frac{\alpha}{\alpha_s} = \frac{P}{P_0}$$

- Where α is the gas content dissolved in the water at the pressure level of test condition; α_s is the gas content dissolved in the water open to atmosphere and P_0 is the atmospheric pressure.

Model experiments - Cavitation Observation Tests

In the full scale:

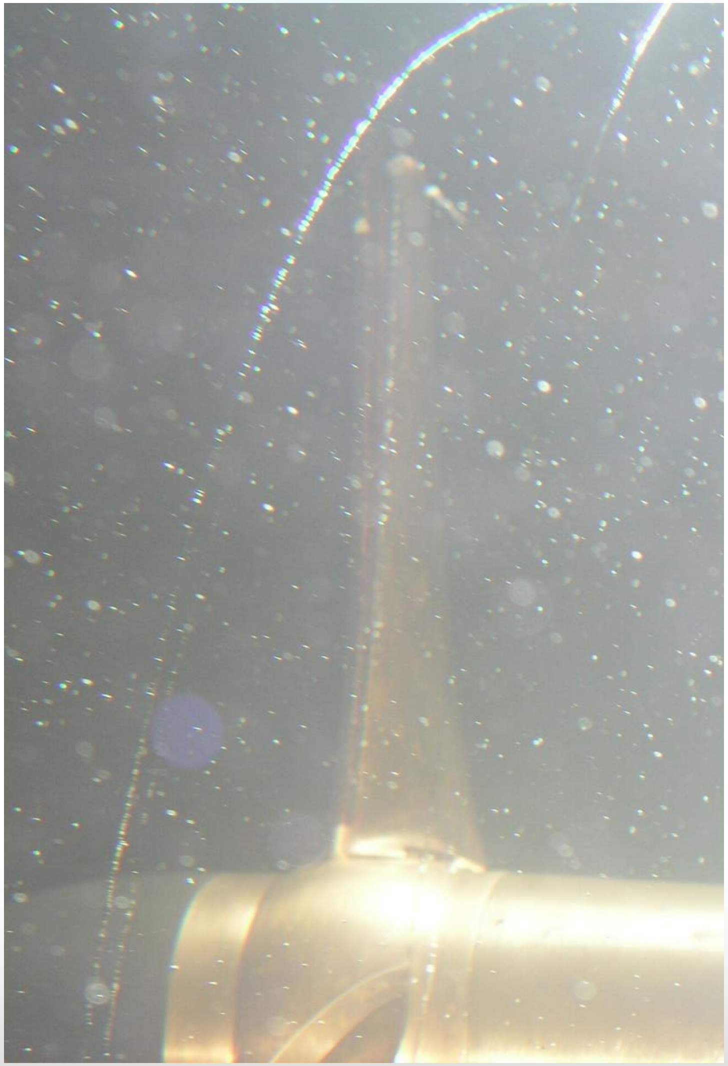
Current speed (m/s):	2.565
Cavitation number:	2.349
RPM:	12
Diameter (m):	20
Shaft immersion (m):	11
Tip speed ratio:	4.9

In model scale:

Current speed (m/s):	1.467
Cavitation number:	2.349
RPM:	342.9
Diameter (m):	0.4
Tunnel Vacuum (mm-hg):	-435
Tip speed ratio:	4.9

During the cavitation observation tests, dissolved air content of the tunnel water was measured to be %35.

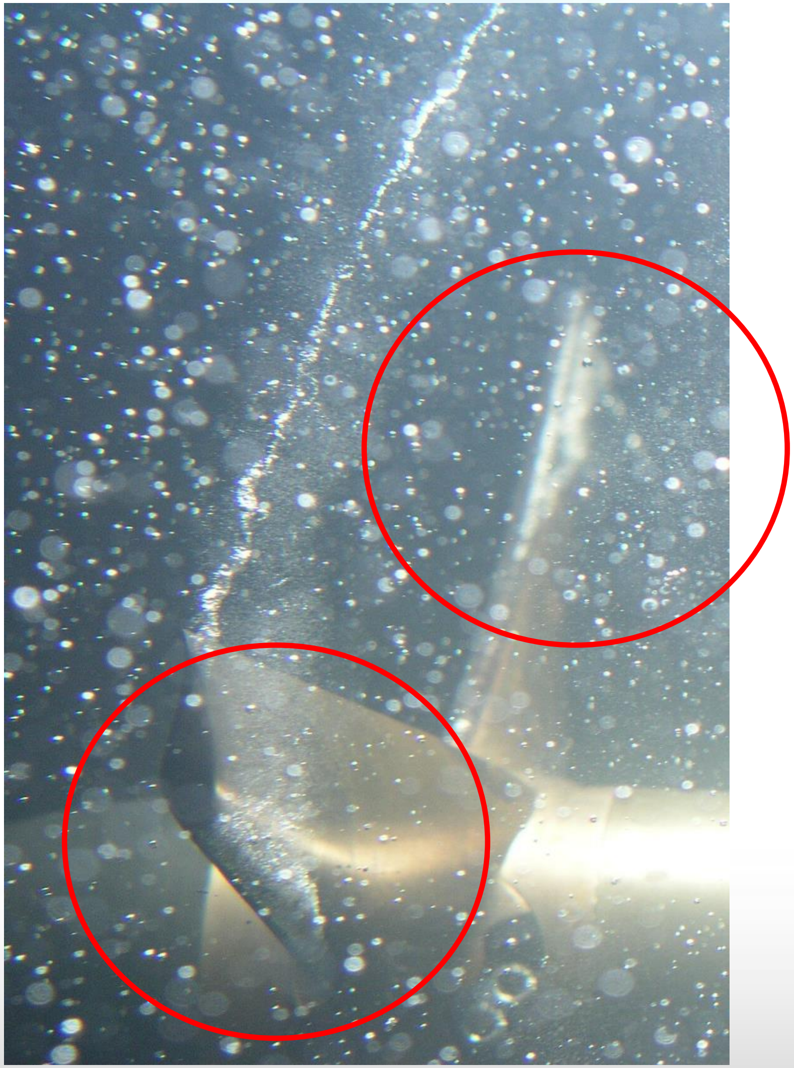
At this particular cavitation condition, only very slight thin tip vortexes were observed.



Model experiments - Cavitation Observation Tests

In the full scale:	
Current speed (m/s):	3.5
Cavitation number:	2.232
RPM:	12
Diameter (m):	20
Shaft immersion (m):	11
Tip speed ratio:	3.591
In model scale:	
Current speed (m/s):	2.0
Cavitation number:	2.232
RPM:	342.9
Diameter (m):	0.4
Tunnel Vacuum (mm-hg):	-435
Tip speed ratio:	3.591

The cavitation test at the condition above resulted in occurance of cloud cavitation covering the leading edge region from approximately 0.5 – 0.9R having a maximum width of 15-20% chord length from leading edge as shown in the figure.



Model experiments - Cavitation Observation Tests

In the full scale:

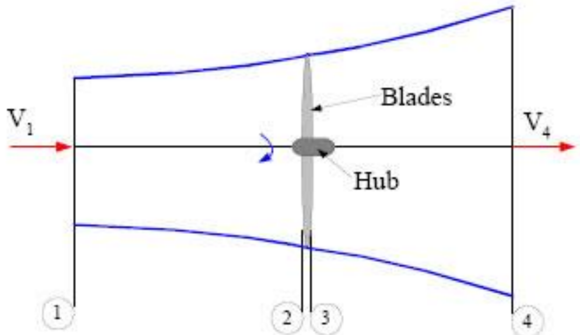
Current speed (m/s):	4.66
Cavitation number:	2.061
RPM:	12
Diameter (m):	20
Shaft immersion (m):	11
Tip speed ratio:	2.7

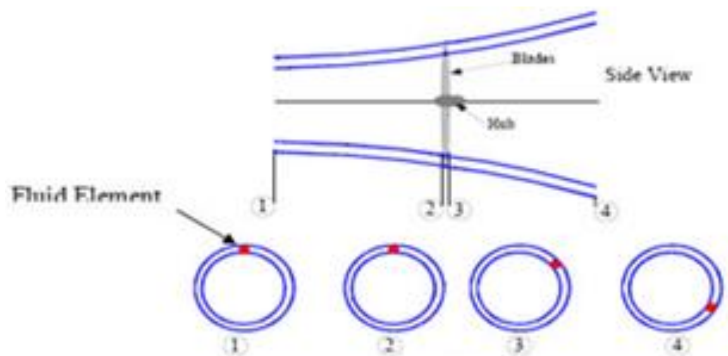
In model scale:

Current speed (m/s):	2.66
Cavitation number:	2.061
RPM:	342.9
Diameter (m):	0.4
Tunnel Vacuum (mm-hg):	-435
Tip speed ratio:	2.7

During this particular test, Strong sheet cavitation covered the leading edge region from approx. 0.35 – 0.9R and at maximum about 30% chord length from leading edge. At the end of the sheet cavitation, slight cloud cavitations and strong burst tip vortexes were also observed.

- The energy absorbed by a turbine rotor can be calculated using 1-d momentum theory -including rotational momentum- by considering the turbine as a frictionless and permeable actuator disk in a control flow stream, bounded by a stream tube [1].





- The presence of the disk induces a drag force on the flow, therefore axial force F_x emerges as a reaction force[3].
- Thus the differential flow through an element can be defined as the product of the pressure difference over the turbine and the area of the region between two concentric circles of different radius[4].
- Rotational effects are introduced by dividing the stream tube into sufficient number of annular elements[4].

Numerical study – Blade Element Momentum Theory in Words

- The blade element theory, on the other hand, is used to model the section drag and torque by dividing the rotor blade into a number of strips along its span-wise direction.

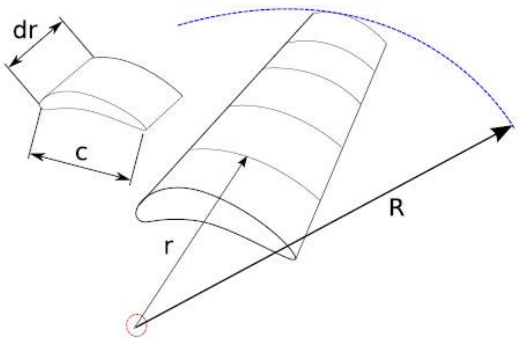
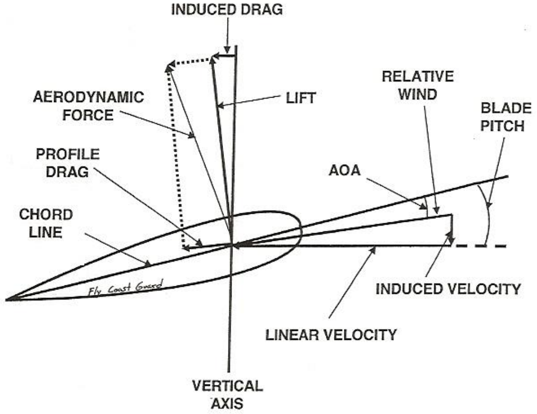


Figure 3



- By combining these theories, at each blade radius (strip), the rotor thrust and power are determined by matching the fluid momentum changes to blade forces based on lift and drag coefficients (C_L and C_D) at certain angles of attack of the blade sections[1].
- The integration of the loadings across the blade allows the derivation of thrust, and power coefficients for the turbine rotor.
- The pressure difference between the suction and pressure sides of a blade gives rise to span-wise flows - which can not be modeled using basic BEM theory. These flows, result in relatively more significant tip loss effects in case of marine current turbines than wind turbine applications. Therefore, certain correction factors[1] needed to be included in calculations[2].

images taken from marinegouge.com

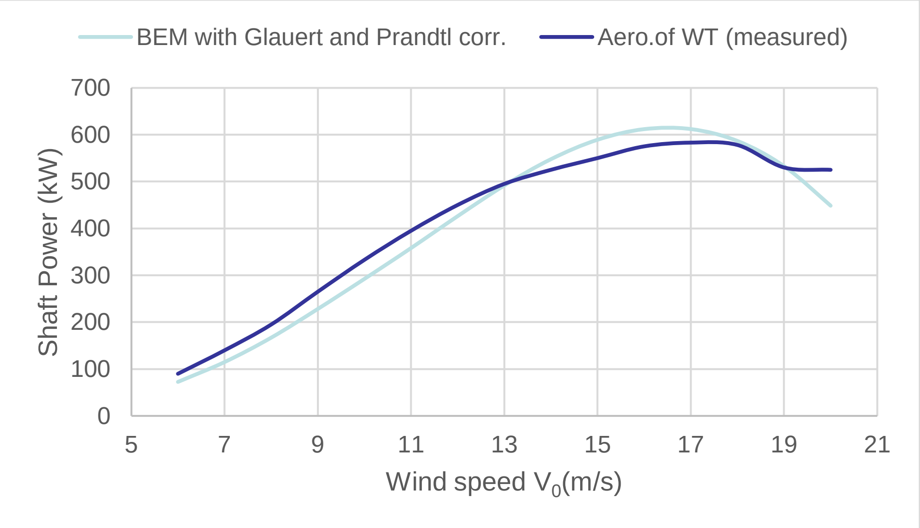
[1]*Prandtl's tip and hub loss correction, Glauert correction.*

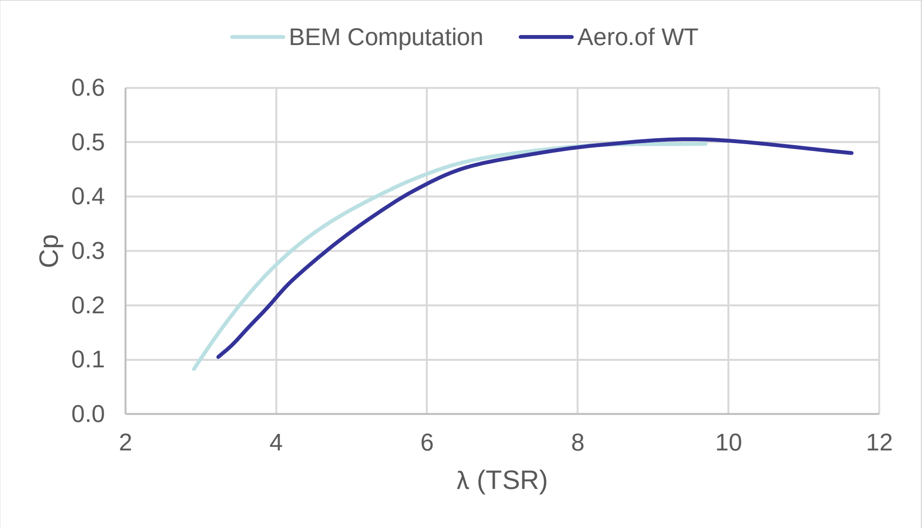
Numerical study – The Analysis of a Wind Turbine via a BEM Code

- To test the accuracy of the numerical method (BEM code) an assessment for a real turbine has been made using the following example of a Nordtank NTK 500/41 wind turbine having parameters below:

Rotational speed: 27.1 rpm; Air density: 1.225kg/m3; Rotor radius: 20.5m;
Number of blades: 3; Hub height: 35.0m; Cut-in/out wind speed: 4m/s - 25m/s.

- The aerofoil data of NACA 63415 is applied along the span.
- The actual geometry and aerofoil data of the blade of the Nordtank NTK 500/41 is not shown here, but the measured power curve and the comparison between the computed and measured power curve is shown in Figures below to give an idea of the accuracy of the model[10].



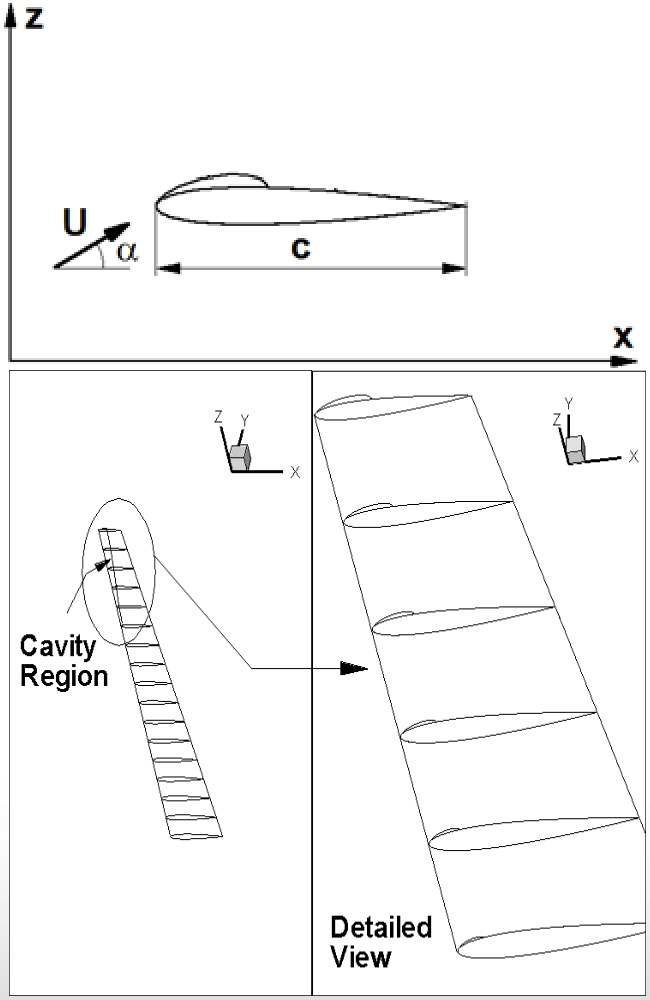


Numerical study – The Effects of Cavitation on Turbine Performance

- Cavitation numbers at different sections (blade angles) are calculated using the cavitation equation mentioned before, for each cavitating section (strip).

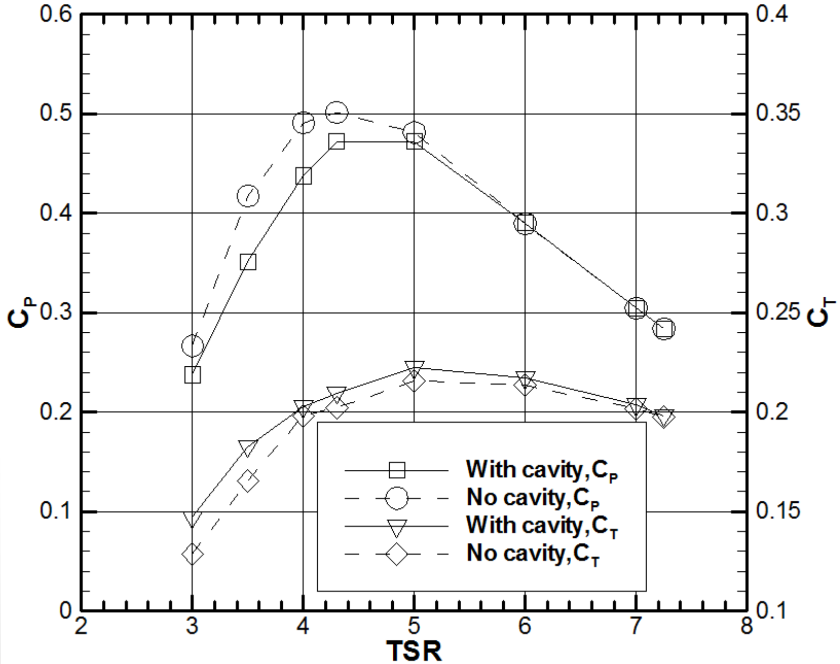
- Then using a panel method code [PCPan], corresponding section geometry – including cavity shape – is achieved. Computed lift coefficients and drag coefficients for the new geometry, using XFOIL code, become the input values for Momentum Blade Element method [12].

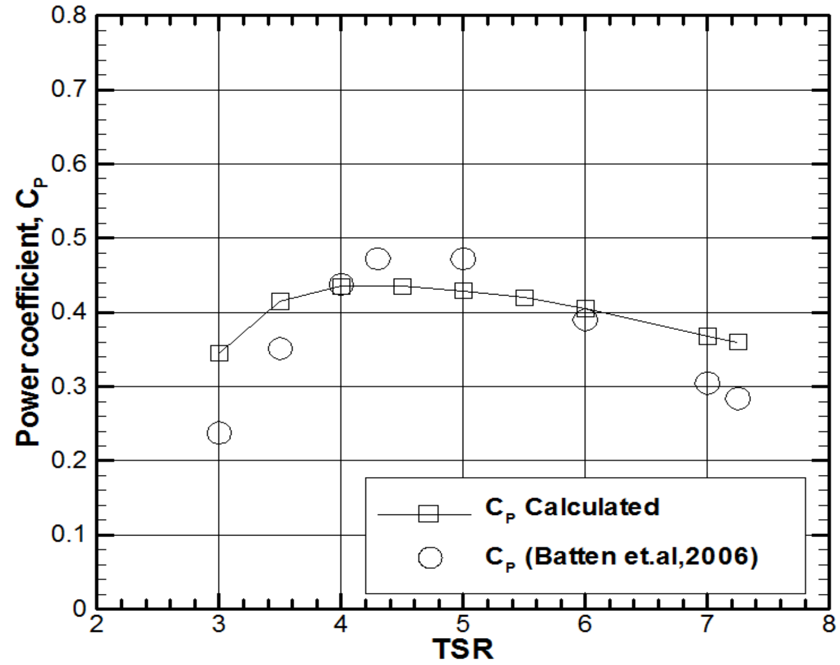
- Fianlly, applying MBE method and integrating the two dimensional sectional characteristics, the thrust and power coefficients versus current speed can be found for a cavitating turbine.



Numerical study – The Effects of Cavitation on Turbine Performance

- Although the differences between the power coefficient values without cavitation and with cavitation are small for higher tip speed ratios, the power coefficient with cavitation is lower than that of without cavitation for small tip speed ratios, figure below-left [13].
- Note also that thrust coefficient values with cavitation are higher than those of non-cavitating case, since the cavitation surface behaves like an added camber (cavity increases the drag coefficient of the section).
- In the figure below-right the calculated power coefficient values versus tip speed ratio, for non-cavitating operation conditions, are compared with those of given in Batten et al., 2006 [13].





Conclusions/Future work

- The power extraction performances of the rotor have been tested and evaluated with different current speeds (2 & 3 m/s) and the power coefficient (representing the efficiency of power extraction) of the rotor is found to be in a reasonable range (about 35-40 %).

- The power coefficients tested with 2 or 3 m/s current speeds are very close to each other. More stable results could be obtained with higher current speed (3 m/s), but rotor might suffer from strong cavitations at low tip speed ratio range for higher current speed.

- The cavitation performance of the rotor was observed at three current speeds, unacceptable very strong sheet cavitations and unstable cloud cavitations were observed at design and higher current speeds, and acceptable stable tip vortex was observed at lower current speed.

- The numerical model was used for analyzing the performance of a wind turbine (or a turbine in a fluid flow free of cavitation) and the results were in accordance with the experimental results.

- Study provided detailed data for the improvement of a design/analysis code based on blade element momentum model which is going to be used to predict the efficiency of turbines operating in cavitation conditions and effects of cavitation on turbine efficiency.

- A 3D model of the turbine is also generated and a CFD study is in progress.

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