A Numerical study on the effect of solidity on the performance of Transverse Axis Crossflow Tidal Turbines

Rónán Gallagher, Carwyn Frost, Pál Schmitt and Charles Young

Abstract— **This paper presents a three-dimensional numerical study employing an actuator line model to investigate the effect of turbine solidity on the performance of a Transverse Axis Crossflow Turbine (TACT). Transverse Axis Crossflow Turbines have a low rectangular form and are ideally suited to relatively shallow tidal and riverine sites due to their ability to handle bi-directional inflow. Lift based TACTs are not well understood due to their complex hydrodynamics when the downstream sweep passes through the wake produced by the turbine shaft and the upstream sweep. The blade loading, hydrodynamics and ultimately power produced during the downstream sweep depends on the number of blades and turbine solidity. This numerical study is carried out using OpenFOAM and replicates planned fieldwork where the turbine performance and in-service blade loading will be monitored as a function of turbine solidity. Turbine solidity is a dimensionless parameter that measures the proportion of blade area to the projected turbine frontal area. Turbines achieve peak performance at an optimum solidity and tip speed ratio. Solidity can be varied by changing the number of blades or changing the turbine radius. An increase in solidity causes the peak performance to reduce and shift to a lower tip speed ratio albeit with a greater torque.**

This paper also explores the effect that maintaining turbine solidity has on turbine performance over a range of typical inflow velocities. Turbine solidity is held constant by varying both the number of blades and turbine diameter. Iso-solidity has been investigated for wind devices but little is known about the effect of maintaining turbine solidity on TACT performance.

Keywords— **crossflow turbine, solidity, blade loading, actuator line modelling.**

I. Introduction

THIS numerical study is a precursor to a planned field study of a Transverse Axis Crossflow Turbines (TACT) where solidity will be varied and turbine performance and blade loading will be monitored. TACTs are a niche subset of lift based hydrokinetic turbines and have a low rectangular profile. A comprehensive review of experimental studies relating to TACTs has previously been carried out by the authors [1]. This review considered some of the key dimensionless parameters that impact crossflow turbine performance and identified trends and insights from the point clouds of data retrieved from the literature reviewed. The experimental studies reviewed in [1] identified a variety of different types of crossflow turbine ranging from the Darrieus turbine, Lucid Spherical Turbine (LST), Gorlov Helical Turbine (GHT) to the Transverse Horizontal Axis Water Turbine (THAWT). Despite the absence of an agreed design consensus for a TACT, trends were identified in the data. In the review, a positive correlation between blockage and tip speed ratio and an inverse relationship between solidity and tip speed ratio were identified. The review also highlighted the absence of fully disclosed experimental work pertaining to crossflow turbines and stressed the need for validated field work in the area of solidity, blockage and hydrodynamic blade loading. Therein, a campaign of numerical and experimental work has been formulated that plans to address some of the shortfalls identified. This paper focuses on the numerical schedule of work and the methodology of the field studies. Results stemming from the planned experimental work will be the subject of future planned publications.

II. Literature review

The hydrodynamics of crossflow turbines are not very well understood. The flow passing through a crossflow turbine is both temporally and spatially complex as the downstream sweep of the blades must pass through the wake of the upstream sweep as well as the wake and shadow of the rotating shaft. Crossflow turbine blades experience rapid oscillations in angles of attack in excess

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Digital Object Identifier: https://doi.org/10.36688/ewtec-2023-273

of their static stall angles in each complete rotation. This oscillation in angle of attack impacts the blade loading in addition to solidity [2].

Turbine performance is influenced by many parameters such as blade profile, chord length, camber and the number and type of blade supports. The influence of each of these parameters on turbine performance is not equal. Also, there can often be a convolving or synergistic effect between several of these influencing parameters which means it can be quite difficult to evaluate the true effect of a single parameter on its own. Included in the long list of influencing parameters are six dimensionless numbers that have a significant bearing on turbine performance. These governing dimensionless numbers include; Reynolds number, Froude number, blockage, number of blades, tip speed ratio and solidity. Blockage is the ratio of the frontal area of the device plus supports and the channel cross section and solidity is the ratio of the total length of blade chords to the turbine circumference.

Solidity

Model or geometric solidity compares the turbine configuration to that of a solid cylinder. Solidity is defined as the ratio of the total length of blade chords to the turbine circumference, as given by (1).

$$S = \frac{nc}{\pi D} \tag{1}$$

According to [3], solidity describes the robustness of the entire turbine shape. Solidity is a very important dimensionless parameter in turbine design and operation. In a standard turbine performance Cp-λ curve, the turbine attains maximum performance at an optimal tip speed ratio. However, solidity is one of the key parameters dictating the rotational velocity at which the turbine will achieve its maximum performance [4]. Therefore, for a given turbine configuration the turbine is operating sub-optimally at all other tip speed ratios. Regulating the tip speed ratio for a turbine in service is complex as the inflow will vary both in magnitude and spatially over time.

An inverse relation between solidity and tip speed ratio was identified by [1] for a varied mix of crossflow turbines as reproduced in Fig 1. In the review of experimental work, it was noted that the optimum TSR decreased in tandem with Cp as the solidity was increased. This trend has also been observed in both 2D and 3D numerical studies.

In a 2D numerical study of a 3, 4 and 5 bladed vertical axis water turbine, [5] found that the coefficient of performance decrease by 6% and 14% for the 4 and 5 bladed device, respectively. This reduction in performance was achieved at tip speed ratios 10% and 20% below the optimum 3 bladed device, for the 4 and 5 bladed device, respectively.

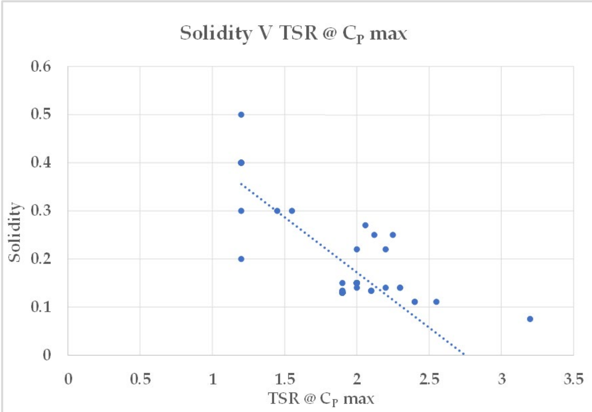

Fig 1. Solidity V TSR for crossflow turbines [1]

In another numerical study on a crossflow turbine, [6] increased the turbine solidity from 0.019 to 0.038 by doubling the number of blades from two to four and found that the shift in peak performance was also to a lower tip speed ratio. In this case, Cp went against the trend and actually increased from 0.43 to 0.53. The increase in the number of blades lead to a reduction in mean streamwise velocity between 14% to 26% which in turn decreased the tip speed ratio. According to [6], the increase in turbine performance was attributed to a decrease in angle of attack due to higher solidity at the lower tip speed ratios which led to an increase in the lift and power generated. It seems unlikely that the increase in peak performance may be attributed to increased lift at lower tip speed ratios. No mention is made of the increase in drag from the additional struts required to support the extra blades and it is not clear if a blockage correction factor was applied to the results.

Iso-solidity

The concept of iso-solidity has been explored by a small number of researchers in the area of both hydrokinetic and wind devices. Reference [7] carried out a series of numerical analyses to investigate the effect of solidity on a straight-bladed vertical axis wind turbine and changed both blade chord and blade number. It was found that VAWTs with large solidity achieved peak performance at lower tip speed ratios. They also found that device configurations with different combinations of blade number and chords albeit with the same solidity adversely effected the turbine performance.

In a lab based experimental study of the characteristics of a Darrieus turbine [8] found that not only selecting the correct solidity for a turbine but also the optimum number of blades is also important. Similar to [7], [8] also found that when the blade chord was changed to achieve a different turbine configuration with the same solidity the turbine characteristics changed as a result of the change in the number of blades and impacted the turbine performance.

According to [9] the number of blades for VAWTs is influenced by several important design factors, such as the uniformity of power output desired as well as structural loads and cost. A smaller chord length and larger number blades at the same solidity yielded smoother loads and power production and the length scale of the load fluctuations was found to be smaller chord length. Reference [10] conducted a 2D CFD analysis of a vertical axis tidal turbine and found that increasing the number of blades from three to four with a fixed solidity led to a slight drop in turbine performance. The drop in performance was attributed to Reynolds number effects.

Reference [11] and [12] carried out a numerical study of a novel crossflow turbine. The turbine comprised three blades on a looped path which meant that some of the wake of the upstream sweep actually passed before the blades on the downstream sweep arrived. Similar to other researchers, it was observed that increasing solidity meant that peak performance was achieved at lower tip speed ratios. Reference [11] increased the blade chord length and found that the mean coefficient of performance was approximately constant for turbine configurations of the same solidity.

Optimal Solidity

It is well documented that the tip speed ratio as which peak turbine performance is achieved decreases as solidity is increased. Each turbine configuration, therefore, achieves maximum performance at an optimum tip speed ratio and optimum solidity. It is argued that the familiar Cp-λ curve for a turbine should also report the optimum solidity at which the maximum performance was attained. The Cp-λ curve should perhaps be presented as a family of curves or a 3D surface with solidity being the third dimension.

Reference [13] explored the concept of optimal geometric design and optimal solidity for a vertical axis wind turbine. They found that for a variable speed device, the optimal solidity at which the peak Cp was achieved decreased as tip speed ratio was increased. In a development of their earlier work, [14] investigated a 2, 3 and 4 bladed VAWT numerically. In this study, they concluded that at a given wind speed when the turbine was rotating at a higher tip speed ratio, the optimal performance was achieved with a smaller solidity, whilst the converse was true if the turbine was rotating at a lower tip speed ratio. Based on the power available in a flow being proportional to the turbine fontal area multiplied by the velocity cubed, $P = f(Au^3)$, [14] defined a new parameter , $\sigma\lambda^3$ to better investigate the invariance of C_p values to solidity and tip speed ratio. This new expression correlating optimum tip speed ratio to optimum solidity, is given by (2).

$$\lambda_{opt} = 2.693\sigma^{-0.329} - 1.605 \tag{2}$$

Equation (2) can be used to either calculate the optimum tip speed ratio for a turbine of given solidity or in reverse to calculate the optimum solidity for a turbine with an optimum tip speed ratio. No expression linking optimum tip speed ratio and optimum solidity exists for TACTs, however, it is evident from Fig 1 that there clearly is a relationship between the two geometric parameters.

Design and Experiential Guidance

A suite of support documents relating to the design and development of hydrokinetic energy devices are available from the International Electrotechnical Commission [15]. The IEC 62600 series of support documents range from IEC TS 62600-2 which specifies the design requirements such as safety factors for marine energy converters to IEC TS 6200-301 for river energy resource assessment [15]. IEC TS 62600-3 offers advice on the measurement of mechanical loads on hydrokinetic devices [16]. According to the standard, "published experience on using load cells, torque transducers and strain gauges for offshore load measurements of MEC deployments is still rare". IEC TS 62600-3 recommends the use of fiber optic strain sensors due to their immunity to electromagnetic interference and cites [17] as the sole case study for implementing this type of strain sensor. Reference [17] utilized fiber optic strain sensors and associated slip ring to measure the strains on a straight three blade vertical turbine with central struts in a laboratory tow tank setting. The tow tank test was completed successfully, and excellent agreement was achieved between sensors at similar locations on different blades. It is reported that these strains were of the same order of magnitude as those predicted by the finite element analysis carried out. Despite the success of the lab work with the fiber optic sensors at the University of New Hampshire tow tank no subsequent publications could be found from the authors of the 2016 publication during the literature review carried out for this paper.

In a laboratory study, [18] investigated the bond integrity between FBG sensors and composite coupons. The coupons were tested under static and fatigue loads in both a dry and wet environment. The soaked coupons were found to suffer from a variety of modes of failure and it recommended that externally bonded FBG strain sensors should be avoided unless with extra environmental protections are put in place.

It is clear that significant time lapses exist between successive publications around condition monitoring of hydrokinetic crossflow turbines. Published experience of offshore load measurements is much needed to improve not only the understanding of load senor response but also their durability for real life conditions. This is particularly pertinent as the marine energy sector grapples with new technologies like fiber optic strain gauges and associated ancillary test equipment. Experiential accounts of even how best to adhere load sensors to turbine devices would be hugely beneficial to the marine energy community at large.

Blade Loading

Full disclosure of the performance and hydrodynamic blade loading experienced by hydrokinetic turbines is very rare as evidenced by [1]. Commercial sensitivities obviously come to the fore as many tidal turbine technologies are very early on the Technology Readiness Level pathway and as a result turbine promoters are reluctant to reveal key information to their competitors. Even if a publication on blade loading is produced the authors tend not to disclose key parameters and normalise any commercially sensitive data. When information is only discussed in relative terms it makes it is very difficult for the research community to replicate results and propose any improvements. One such example is the study by [17] referred to earlier whereby the mean strain measured was reported to be of the same order of magnitude as the finite element analysis. Much more benefit could be accrued by the research community if both the expected and actual micro strain were reported accompanied by a commentary to explain the difference between the values.

The reluctance of turbine developers to publish details of studies on in-service blade loadings is understandable, however, there is an insatiable demand for electricity and alternate sources of electricity are urgently required. Therefore, any stories of success or otherwise regarding blade loading or the instrumentation used would be gratefully received by the marine energy community. A rare example is that by [19] whereby the successful deployment of thermoplastic blades is presented along with a number of lessons learned as result of major errors of inadequate quality assurance and quality control relating to the instrumentation and data acquisition system. The turbine in question was deployed and successfully operated for three months however very little data (approximately 4 hours) was actually recorded due to a coding error in the data acquisition system. Another good example of lessons learnt is that by [20] in their account of strain measurements of a full scale 3 bladed HATT device in both parked and generating positions. In their work, blade strains, torque and thrust were measured and the need for synchronised recording systems was highlighted.

III. TEST CAMPAIGN

Solidity was chosen as the primary parameter for this research in order to utilise the natural field test facilities in Strangford Lough adjacent to the Queen's Marine Laboratory in Portaferry. In addition, a bank of experience relating to small scale turbine testing is available from the marine services operator locally. To this end, a robust TACT with a maximum diameter of 1m and straight blades of 1m length was specifically designed to operate in a Reynolds independent flow regime with inflow speeds up to 3m/s with Reynolds chord number, Re_{chord}~10^6. The turbine was designed to be used in a series of push tests suspended over the front of the test vessel by a gantry of space trusses as shown in the proposed deployment configuration in Fig 2. The turbine has straight blades of NACA0020 profile and chord length of 95mm. The turbine and blades are shown in Fig 3 and Fig 4, respectively. The turbine frame is made from mild steel and the turbine blades were made from a composite blend with a Youngs modulus of approximately 70GPa. The rotating drum comprising the blades and end disks are connected to the drivetrain above the waterline via a toothed belt and associated pulleys with a 2:1 ratio. The pulley is protected by a pulley guard as shown in Fig 3. The drivetrain in turn will be connected to the data acquisition unit on the boat deck. All energy generated during the field trials will be dumped via load resistors. The space trusses cantilevered from the boat will also be used to position the flow measuring devices at the requisite spacings and secure the cables leading from the device. Provision has also been made for a system of cross bracing in case the turbine begins to shake or encounters resonance during testing. The partially assembled TACT with the pulley guard attached is shown in a reclined position in Fig 3.

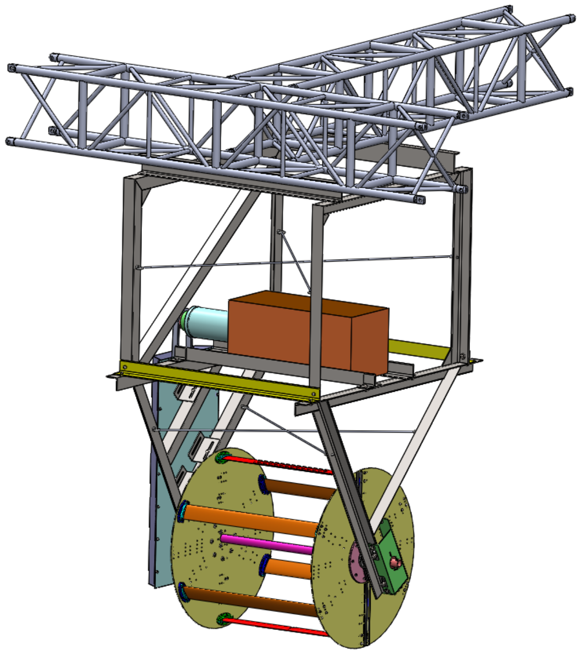

Fig 2. TACT CAD model and proposed deployment configuration.

Fig 3. Partially assembled TACT at Queen's Marine Laboratory workshop, Portaferry with pulley guard attached.

The turbine was designed to accommodate a maximum of six blades at turbine diameters of 0.5m, 0.75m and 1m, as shown in the CAD model of the end disks in Fig 5. The end disks contain many holes to accommodate cables running from the externally bonded strain sensors, different turbine diameters as well as facilitating blade mounting at both ¼ and ½ chord positions. Table I lists the complete test matrix of numerical simulations and planned field tests.

Fig 4. NACA0020 composite blades fitted with blade end clamps to attach to the end disks.

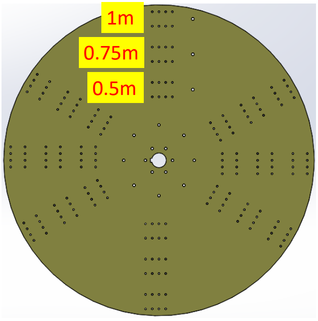

Fig 5. End disk CAD model which can accommodate a maximum of six blades at turbine diameters of 0.5m, 0.75m and 1m.

TABLE I
NUMERICAL AND EXPERIMENTAL TEST MATRIX

Test No.	No. of blades	Turbine diameter (m)	Solidity (-)
T1	1	1	0.03023
T2	2	1	0.06047
T3	3	1	0.09071
T4	4	1	**0.12095**
T5	6	1	**0.18143**
T6	1	0.75	0.04031
T7	2	0.75	0.08063
T8	3	0.75	**0.12095**
T9	4	0.75	0.16127
T10	6	0.75	**0.24191**
T11	1	0.5	0.06047
T12	2	0.5	**0.12095**
T13	3	0.5	**0.18143**
T14	4	0.5	**0.24191**
T15	6	0.5	0.36287

Values of constant solidity are highlighted in bold.

During the field study all data logging devices will remain on the boat deck. Turbine performance will be measured with a torque sensor rotary encoder and the blade loading will be determined from the blade strains. The blade strains will be detected by a series of Fiber Bragg Grating (FBG) strain sensors bonded to the blade surface. The externally bonded FBG strain sensors will be sealed in hot coat epoxy protective layer to guard them from the harsh environment. The FBGs will in turn be connected to the interrogator through a fiber optic rotary joint.

IV. NUMERICAL STUDY

This study employed a coupled actuator line model (ALM) and finite element analysis tool with one way fluid structure interaction developed by [21]. Fully resolved geometric models that are exact representations of the real device are possible but can take quite a long processing time. ALMs were originally developed by [22] to simplify modelling and CFD processes around wind turbines. In a blind test of three bladed horizontal axis wind turbine in a wind tunnel by [23], an ALM yielded similar values to fully resolved geometric CFD solutions. In a series of tow tank experiments, [24] reported very good agreement between the ALM and experimental results for the high blade solidity (c/R=0.28) UNH Reference Vertical-Axis Turbine and the medium solidity (c/R=0.07-0.12) Sandia Labs Reference Model 2.

Actuator line models have shorter processing times in comparison and are gross simplifications of the real device that effectively lumps forces at nodes defined by the operator. ALMs are ideally suited to long slender elements such as blade profiles whereby the blade is simulated as a line and the 2D lift and drag coefficients are attributed to each individual actuator line element. The tool developed by [21] combines actuator line theory with a finite element beam model to simulate flexible structures under fluid loads wherein inflow dependent reaction forces are applied to the fluid domain.

AL models use a dynamic stall model to capture the force coefficients at high angles of attack. Various dynamic stall models are available and described in detail in literature. The OpenFoam library turbinesFoam as used in this study, utilises a Leishman-Beddoes dynamic stall model. The amplitude and direction of the incoming flow are important factors that impact the dynamic stall model used. turbinesFoam evaluates the amplitude and direction of the incoming flow by interpolating the current location of interest from neighbouring cell centres. It is likely that other and perhaps better methods exist in literature, and it is hoped to implement and test them in the future. All AL models will struggle to simulate dynamic stall conditions correctly. It is hoped that the experimental data gathered during the field trials will help to quantify the modelling error and support the search for better models.

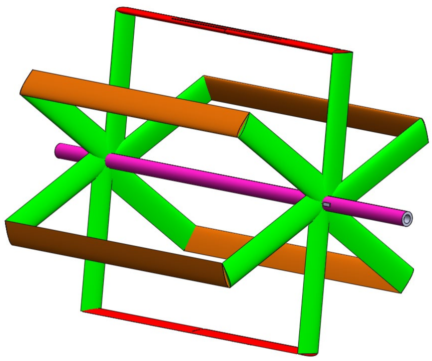

Fig 6. Six bladed TACT configuration employed in numerical simulations. None of the elements of the submerged support frame were included in the numerical study.

In this study the solid end disks which support the TACT blades were replaced with struts of the same NACA0020 profile and 0.095m chord length as the blades. A typical idealised model employed in this study comprising six blades, support struts and shaft is shown in Fig 6. Some details of the numerical simulations carried out are listed in Table II.

Lift and drag data for many modern NACA profiles can be notoriously difficult to establish. As a result, the lift and drag coefficients relating to the NACA0021 profile were used in lieu of the NACA0020 profile in this study.

The top surface of numerical wave tank incorporates free boundary conditions as described by [25] and [26]. The numerical domain used in this study was 20m long, 5.4m high and 6m wide. The turbine axis was located centrally in a lateral direction and 8m from the inlet. Imitating the field test scenario, the turbine shaft was located 1m below the free surface. The turbine rotated within a refined region within the larger numerical domain. The diameter of the refined rotating region was kept at 0.6m for all simulations carried out. The cell size of the outer static domain measured approximately 0.2m in each direction.

TABLE II
NUMERICAL MODEL DETAILS

Element	Details
Blade	NACA0020, 14 elements
Strut	NACA0020, 6 elements
Shaft	50mm dia. tube, 20 elements
Inflow velocity	1m/s
TSR	1.25 - 2.75
Refined region (rotating)	0.6m dia.
Outer region (static) cell size	0.2m * 0.2m * 0.2m
Timestep	0.001s
Run time	10s
OpenFoam library	turbinesFoam

The numerical study carried out is a simplification of the TACT turbine. No attempt has been made at this point to quantify the implicit losses that will inevitably be encountered in the field. Examples of losses that will be experienced include mechanical and system losses during the conversion of kinetic energy in the flow to electrical energy in the drivetrain as well as the inertia of the turbine drum, pulley belt and drivetrain assembly. Post field trials it is planned to quantify the system losses in the workshop and make allowances for these in the power estimates achieved during post processing.

Preliminary Numerical Results

Each of the simulations were run for 10s and turbine performance data was gathered when the turbine model was in steady state. The mean coefficient of performance for a 0.75m turbine with three blades for various levels of mesh refinement is shown in Table III. As the mesh refinement and number of cells is increased the mean coefficient or performance begins to plateau. It is important to note that the mesh refinement level could have been increased further. However, the rationale for this numerical study was to use the actuator line method and gather turbine performance data with short simulation periods. Consequently, it was decided to use mesh level 4a for all the simulations in this study.

TABLE III
MESH CONVERGENCE

Mesh No.	No. of cells	$\overline{C_p}$
3	152,680	0.200721
3a	263,200	0.191965
4	658,280	0.163286
4a	768,800	0.157731

Each of the planned tests listed in Table I have a unique configuration and therefore have their own Cp-λ curve. The mean Cp-λ curve was generated for each configuration with mesh level 4a from tip speed ratio of 1.25 to 2.75 in 0.25 increments as shown in Fig 7. It can be seen in the figure that not all the simulations executed at each tip speed ratio. For example, T15 comprising six blades with a turbine diameter of 0.5m only successfully executed at tip speed ratios of 1.5 and 1.75. Important lessons such as this will inform the field studies as to which of the proposed test cases planned in Table I are more likely to run.

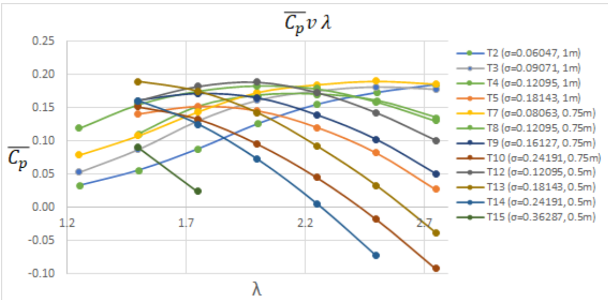

Fig 7. $\bar{C}_p - \lambda$ study employing mesh level 4a for all TACT configurations as specified in Table I for λ tip speed ratios from 1.25 to 2.75

Although the overall trends of the effect of increasing solidity can be observed in Fig 7, the overall plot is quite busy. Therefore, for the purpose of clarity, the individual mean Cp-λ plots for turbines of 0.5m, 0.75, and 1m diameters are shown in Fig 8, Fig 9 and Fig 10. In these component plots the effect of increasing turbine solidity can be observed much more clearly.

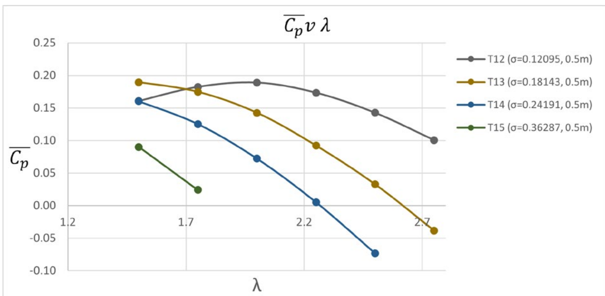

Fig 8. $\bar{C}_p - \lambda$ study subset of all 0.5m TACT diameters for tip speed ratios from 1.25 to 2.75

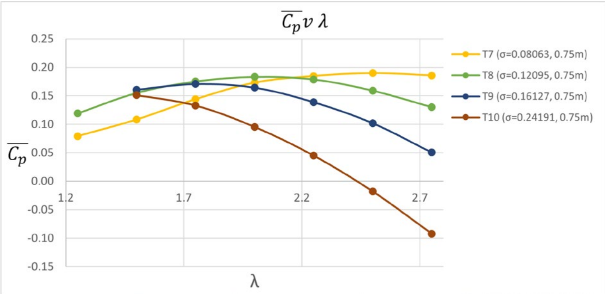

Fig 9. $\bar{C}_p - \lambda$ study subset of all 0.75m TACT diameters for tip speed ratios from 1.25 to 2.75

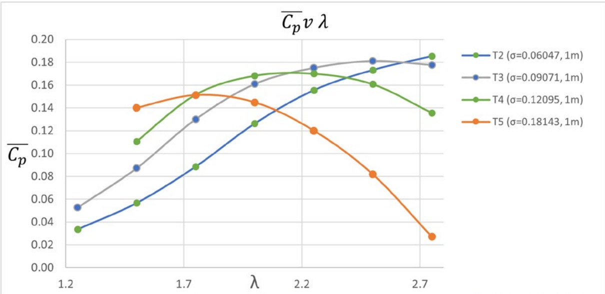

Fig 10. $\bar{C}_p - \lambda$ study subset of all 1m TACT diameters for tip speed ratios from 1.25 to 2.75

A subset of Cp-λ curves for three bladed turbines with diameters ranging from 0.5m to 1m is shown in Fig 11. Once again, it can be seen in Fig 11 that as the diameter is reduced and the solidity is increased from 0.09071 to 0.18143 the tip speed ratio at which maximum performance occurs reduces. This result is in line with those discussed earlier from literature. As the solidity increases the characteristics of the turbine transforms from lift to drag.

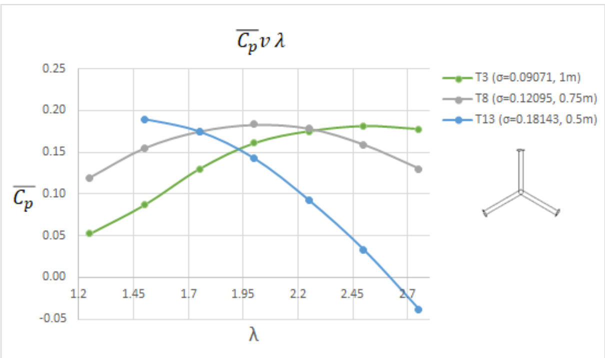

Fig 11. $\bar{C}_p - \lambda$ study for a 3 bladed TACT of different turbine diameters and solidity.

Iso-solidity is explored for $S = 0.12095$ and $S = 0.24191$ in Fig 12 and Fig 13, respectively. Each of the three different turbine configurations in Fig 12, T4, T8 and T12 with 4, 3 and 2 blades, respectively achieve approximately the same value of peak performance. In a similar vein in Fig 13, T10 with six blades and T14 with 4 blades also closely match each other. The fact that turbine configurations of similar solidities and different turbine diameters achieve similar peak performance is surprising. The turbulence generated by the rotating turbine shaft must be negligible as there is no marked decrease in mean performance due to the change in turbine diameters and subsequent reduction in spacing between the upstream blade, turbine shaft and the downstream blades. From the perspective of the water the same amount of area is blocked due to the turbine solidity, therefore the power output should be the same. However, it could also be expected that the turbine configurations with more blades in the water would increase drag, reduce the flow of the water passing through the turbine and therefore reduce peak performance.

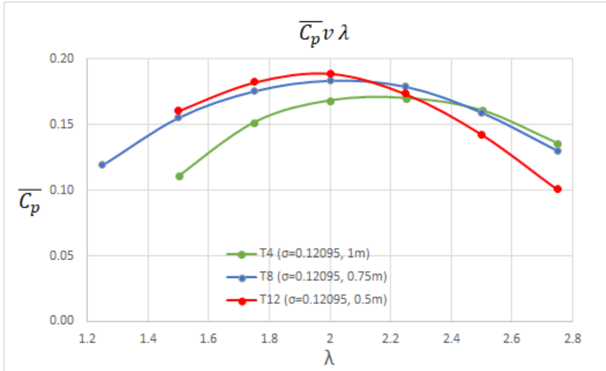

Fig 12. $\bar{C}_p - \lambda$ for turbines with constant solidity, $S = 0.12095$

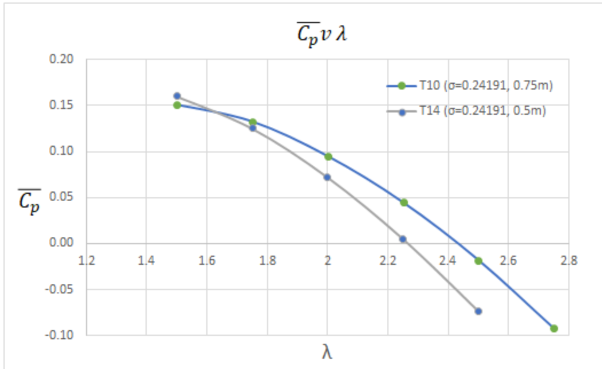

Fig 13. $\bar{C}_p - \lambda$ for turbines with constant solidity, $S = 0.24191$

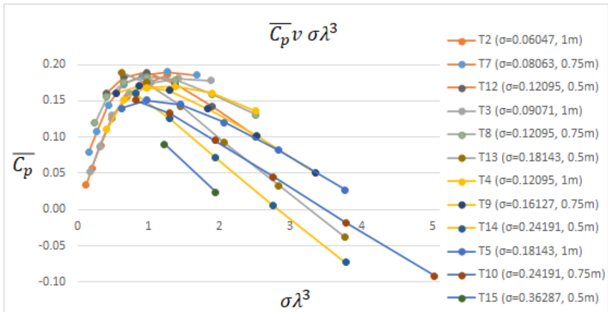

Fig 14. $\overline{C_P} - \sigma\lambda^3$

Emulating the work of [14], the mean performance was plotted against the newly defined quasi power parameter to estimate the power available in a flow, $\sigma\lambda^3$, is shown in Fig 14. The $\overline{C_P} - \sigma\lambda^3$ plot approximately collapses onto a single curve and demonstrates that the $\sigma\lambda^3$ value corresponding to optimal performance, is almost independent of the number of blades and solidities.

It is hoped that the data gathered during the field work will also collapse onto the same curve thereby reinforcing the concept that peak turbine performance occurs at optimum tip speed ratio and optimum solidity.

V. Discussion

Turbines achieve peak performance at both an optimum tip speed ratio and optimum solidity. A typical mean Cp lambda curve for a turbine should be presented as a family of curves or a 3D surface with the coefficient of performance being plotted as a function of both tip speed ratio and solidity.

Wind turbines adapt the pitch of their blades in response to a change in the inflow. Tidal turbines should also be able to adapt in a similar fashion. Akin to maximum power point tracking utilised in some generators to control the turbine rotational speed, straight bladed TACTs could be installed with their own flow measurement and condition monitoring system. An onboard condition monitoring system would enable the turbine to respond to the local conditions. If the inflow conditions changed quickly, then the change in inflow could be detected and assessed by the onboard control system. The onboard turbine controller could then manoeuvre the turbine blades to maintain optimum solidity thereby achieving maximum performance for the given inflow conditions. It could also be possible that TACTs could have a configuration with blades at different radii depending on what is required at any given time. Allowing for intelligent turbine controls, turbines could even have active or passive blades. Depending on their position, active blades would generate power and the passive blades could simply be aligned with the flow.

Tidal turbines will inevitably experience extreme loading during their lifetime in-service which was not anticipated by the designers. Flexible turbine blades are being promoted some researchers, such as [3] and [27] as being a possible solution to cope with extreme loading events. An intelligent onboard controller could anticipate extreme loading events and minimise the likelihood of any damage as a result. In this scenario turbine blades could simply be oriented to the inflow and reduce frontal area to the oncoming inflow.

VI. Conclusion

Solidity is sometimes overlooked but nevertheless is a key dimensionless parameter in hydrokinetic turbine design and operation. All of the studies reviewed in this paper changed either the number of blades or the blade chord length when they were changing turbine solidity. None of the studies reviewed changed the turbine diameter.

It was shown in this study using an ALM that increasing solidity by decreasing the turbine diameter results in a decrease of the mean peak performance and reduces the tip speed ratio at which the peak performance is achieved. This result is in line with other numerical studies and will be compared with field trials in next phase of the overall study. However, what is different in this study is that solidity was changed by changing the turbine diameter unlike all the publications cited in the literature review. This result would indicate that increasing solidity by either increasing the number of blades as in the literature or changing the turbine diameter has the same overall effect. This is surprising as the distance between the upstream sweep, turbine shaft and downstream sweep is halved from T4 to T12. The turbulence experienced by the downstream sweep during T12 should greater than that during T4. An increase in turbulence would normally lead to a decrease in power produced. The power produced by the blades during the downstream sweep must therefore be relatively small in comparison to that produced during the upstream sweep. It is hoped that the hydrodynamic loading experienced by the blades and the amount of power produced over a complete revolution will be determined by the FBG strain sensors during the Strangford Lough field trials.

Constant solidity was also explored in this study. It was observed that turbines with the same solidity albeit with different numbers of blades and turbine diameter all achieved approximately the same peak performance. In the literature review an expression was discovered that quantified the relationship between optimum tip speed ratio and optimum solidity for vertical axis wind turbines. A similar expression will be developed for TACTs once the data from the field trials is processed.

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