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Hydrodynamic Effect of Highly Skewed Horizontal-Axis Tidal Turbine (HATT) Rotors

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Abstract: While hydro turbines generate over 40% of the world's total renewable energy, these traditional turbines present a great environmental concern due to the potential of their sharp blades to damage aquatic lives and ecology, along with their harmful noise and vibration during operation. One effective solution to these environmental issues is to substantially increase the skew of these blades, which would result in a much safer blade operation for aquatic animals (such as fish, etc.) and a substantial reduction in noise and vibration. Adding skew to turbine rotors is known to reduce cavitation and noise, and hence, to mitigate the environmental impact on underwater fauna and flora. However, adding skew will compromise the power performance of the turbines. This study aimed to identify the effect of rotor skew on the hydrodynamic power performance of a series of horizontal-axis turbine rotors that were manufactured using 3D printing technology and tested in a towing tank. The diameter of the turbine rotor model was 0.3 m and the skewed angle contained positive and negative angles of 45, 60 and 90 degrees along with a non-skewed rotor. This study was conducted to analyze the hydrodynamics of a turbine rotor with different skew angles and a 0-degree skewed rotor. Various tip speed ratios, ranging from 2.3 to 4.3, were set in accordance with the RPM and the carriage speed. Gain and filter were applied to boost the signal, and post-calibration was conducted. The results show that (1) the non-skewed rotor had the highest power coefficient; (2) the rotor with a skew angle of 45 degrees had the lowest power loss, at 6.97%, compared with the zero-skew rotor blades; (3) while the larger the skew, the more loss in power production efficiency, the rotor with a negative 90-degree skewed angle had the largest power loss, 31.42%. It was then concluded that, based on the results and analysis, (1) to achieve the greatest reduction in noise and vibration, the rotor with a skew angle of 90 degrees would be the best choice, and (2) to mitigate noise/vibration and efficiency due to skew, the rotor with a skewed angle of 45 degrees would be the best design choice.

Keywords: highly skewed turbine rotor; horizontal-axis tidal turbine; uncertainty analysis; renewable energy; environmentally friendly; experimental; towing tank

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1. Introduction

New environmental concerns have been increasingly obvious and remain an urgent issue to resolve. One such environmental concern is the impact on and damage to flora and fauna bought about by the operation of tidal and hydraulic turbines. Adding skew to a propeller blade is a well-known and effective solution to reducing noise, vibration and cavitation without substantially sacrificing its efficiency [1]. As global warming continues to worsen, transitioning from non-renewable energy to a more environmentally friendly alternative is the best solution. Therefore, many studies have been performed to investigate various renewable energy resources as sustainable alternatives. One study showed that a tidal turbine can generate the same amount of energy as a wind turbine four times its size [2].

Tidal currents are bi-directional, and thus horizontal-axis tidal turbines are designed to operate either unidirectionally or bi-directionally [3]. Tidal forces are periodic variations in gravitational attraction exerted by celestial bodies. These forces create motions or currents in the oceans. As water has greater energy density than air, marine turbines can be built smaller than wind turbines. Additionally, tidal power is much more predictable than wind power, which makes it a better source of electrical energy for feeding the electrical grid.

Tidal turbines are designed in such a way as to generate as much energy to convert into electricity as possible. As demonstrated by Frenkel [4], water velocity is much slower on the seabed (boundary layer) and faster near sea level, indicating there is more energy near the surface than the seabed.

Propeller turbines with fixed blades was deemed not to be directly used in reversible tidal flow or shallow water sites [4]. However, the propeller turbine is a proven technology from the wind turbine industry, being the subject of much research; thus, the wind industry suggested that the propeller turbine is in principle more efficient compared to other types of turbines, such as cross-flow turbines [5]. Cross-flow turbines have been found to operate with lower efficiencies due to the destructive interference of the upstream and downstream passages. Nevertheless, they have greater theoretical potential for energy extraction than axial flow turbines at the same turbine diameter due to their larger projected frontal area, and thus intercept a greater energy flux in the undistributed stream, as well as having more effective blockage. Additionally, the design of cross-flow turbines allows the formation of a single long turbine array, which may reduce the installation and maintenance costs [5]. However, the flow physics of cross-flow turbines in confined flow conditions has not been fully investigated. Therefore, propeller turbines are still preferred.

Natural frequency is the frequency at which a body vibrates when excited by external or by internal force. Although the structure offers the smallest amount of resistance, failure can occur if left uncontrolled. When cavitation occurs, it generates noise and vibration in turbines. Cavitation will most likely not occur in a turbine rotor, including most of the tidal turbine rotors investigated in this study, because their cavitation number is usually large [3]. There have been some previous studies on cavitation of tidal turbines, but the particular geometry of the turbine blades, the water depth, the operation pressure on the suction side of the rotor blades and the key indicator of cavitation, the cavitation number, were not seen to be taken into account [6]. This study shows that the blades of a tidal turbine may be exposed to cavitation over relatively long periods of time during their service life, although deterministic analysis predicts that cavitation inception is not possible. Thus, there is a possibility that vibration due to cavitation will affect the rotor as well. Vibration can also affect the efficiency of the rotor. Moreover, vibration can cause noise, and thus affect marine life. Marine life is extremely sensitive to noise pollution, due to their reliance on underwater sounds for basic life functions, such as mating and searching for food, and an absence of any mechanism to safeguard them against it. Animals exposed to underwater noise for hours at a time are at high risk for injury or death; for example, whales beaching themselves shortly after a tactical sonar exercise is a rather common effect of noise pollution, and this has been reported in regions such as Greece, Madeira, Hawaii, Spain and coastal U.S. areas where sonar exercises are common [7].

A skewed propeller is the most effective design parameter in reducing propeller-induced vibration without sacrificing efficiency. However, excessive skew can cause higher hydrodynamic loading on the blades; hence, an increase in the propeller skew angle may result in generating cavitation in the reloaded blade elements [8]. In a previous similar research project by Hakaran Cheema, a series of highly skewed propellers were analyzed. The results indicated that the thrust and torque values decreased when the skew angle excessively increased [9]. Additionally, Hakaran's project partner, Yiming Yuan, stated that the open-water propulsion efficiency of a highly positively skewed propeller is higher than that of a negatively skewed propeller [10].

For unsteady bearing forces, the radial distribution of skew is the most important factor, since the cancellation of unsteady loading on the blades from root to tip is the mechanism by which skew reduces unsteady bearing forces. The effect of radial distribution of skew on bearing forces can be evaluated using the unsteady lifting surface theory. This theory has been validated with experimental results obtained for a series of skewed propellers operating in simplified wake patterns generated by upstream screens.

There are many types of tidal and hydraulic turbines, for example, the classic horizontal-axis turbines, hydraulic turbines, vertical axis turbines and a recent invention by Sazonov et al., so-called mesh turbines [11,12]. Horizontal-axis turbines are most widely deployed in the tidal energy sectors, and hence, are the subject of this investigation.

The aim of this study was to mitigate the environmental impact of tidal and hydraulic turbines on fauna and flora. The environmental impact is created by noise and vibration during the operation of the rotor blades. The most feasible and effective solution to reduce the noise and vibration, and hence, their environmental effect is to add skew to the turbine rotor blades. The higher the skew, the greater the reduction in noise and vibration. However, the trade-off is that the higher the skew, the lower efficiency. This study aimed to find the correlation between skew and power generation efficiency, and provide a useful reference and firsthand experimental data for turbine designers and researchers in turbine research and design. The results and conclusion are also expected to be a useful reference for the owners of power generators.

In this research project, different skew angles of turbine rotors were investigated in terms of their hydrodynamics instead of skewed propellers, although turbine rotors can be designed such that they are similar to propellers. There are numerous horizontal-axis wind and turbine rotor performance evaluation studies; however, few publications have contained a complete suite of geometry and motion data that can be used to generate the same geometry, repeat the same motion parameters and physically or numerically obtain the same results. Additionally, few research papers have been conducted on skew turbine rotors, another motivation behind this research. Moreover, skew can reduce the impact of turbines on the environment by minimizing noise and vibration, thus allowing turbines to be more environmentally friendly while generating renewable energy. Therefore, this report provides manufacturers and researchers with a reference and option for future renewable energy development or improvement. The power coefficient curve and thrust/drag coefficient curve are included to indicate the efficiency of the rotors.

2. Materials and Methods

This was an experimental study incorporated with numerical predictions. Though the test measurements were obtained for tidal turbine rotors, the testing program for the turbine rotors explored in the current study was the same as that used for traditional propellers. The particular interest of this study is to determine the effects of rotor blade skew on power generation performance. While there have been too many previous studies on marine propellers to mention, to the authors' knowledge, this was the first investigation on the blade skew effect on tidal turbines' energy generation performance.

The experimental testing program was carried out by (1) firstly determining the number of skew variations based on the turbine rotor geometry of a rotor, which was hydrodynamically optimized in the previous studies by Liu and Bose and Liu et al. [3,13]; (2) manufacturing a series of skewed turbine blades using a fast-prototyping 3D printer; (3) calibrating the propeller dynamometer to reduce the uncertainty of the measurement to a minimum; (4) determining the required data points, and hence, the run matrix that is the basis of resource estimates, in terms of the running time and facility time/cost; (5) acquiring the necessary data by measuring the key values of the thrust and drag, and hence, the power and drag coefficients; and (6) conducting analysis and drawing conclusions based on the obtained measurements along with an uncertainty analysis.

The test measurements were taken using the same sampling rate and motion parameters as the ones used in Liu et al. [13]. For details on the testing rig (i.e., the opens boat) that was used to obtain the testing results, see Liu et al. [13]. The data were analyzed in terms of the effect of the blade skew on the hydrodynamic performance of the rotors, especially on the torque coefficient, which could be directly converted using the formula developed in Liu and Bose [3]. An uncertain analysis was also conducted following the guidelines of ITTC [14].

The following sections discuss the details of the main directions of the research, in terms of the design, conduction and data analysis of the current study.

2.1. Turbine Rotor Model

Skew is defined as the angle between a line that is drawn through the hub center and a point located in the mid-chord position of a particular section and the directional line, as shown in Figure 1. Highly skewed is when a propeller's or rotor's blade sweeps back sharply.

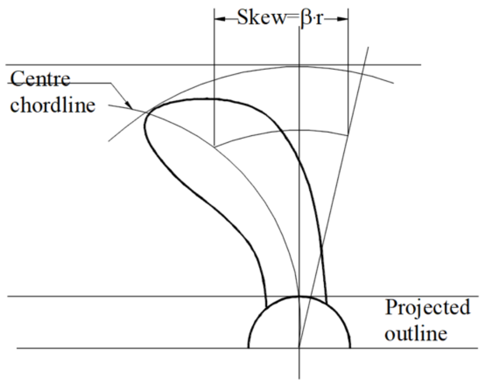

Figure 1. Definition of skew.

A total of seven turbine rotor models with a radius of 0.15 m were designed and 3D-printed for testing in the towing tank. Three positively skewed and another three negatively skewed rotors with the same angle and one turbine rotor with no skew were printed. The planform and sectional offset of the 0-degree-skewed rotor (R0) are shown in Table 1 (geometry of positively and negatively skewed turbine rotors is currently confidential). All rotors were printed using Creality CR-10s and PLA+ (eSun) as the material with an infill density of 100%. To ensure the surface of the rotors remained as smooth as possible, a soft filling and colored spray paint was used to fill the holes and gaps to create a relatively smooth surface. Each turbine rotor weighed approximately 0.28 kg before testing. Table 1 shows key information about the turbine rotor models, and the model can be seen in Figure 2.

Table 1. Key information about turbine rotor models.

Rotor Number	Degree	Rotation Direction	Infill Density
R0	0	-	
R1	45		
R2	60	Positive	
R3	90		100%
R4	45		
R5	60	Negative	
R6	90		

Table 2 shows the key geometric data that was used to generate the rotor geometry, as an example for a zero-degree skew.

Table 3 and Figures 3 and 4 below provide the dimensions of the HATT rig shaft, keyway and the recess on the rotors. As shown in Figure 5, the areas around the recess and shaft hole and keyway were all chamfered to protect the model from damage, increasing the effort needed to install and uninstall the rotor on the shaft. The diameter of the hub, shaft hole, recess and keyway were designed such that there is space for printing errors, as

3D printers tend to print larger on the exterior and smaller on the interior, thus reducing the time spent sanding the model to adjust the dimensions after printing so that it fits smoothly on the shaft.

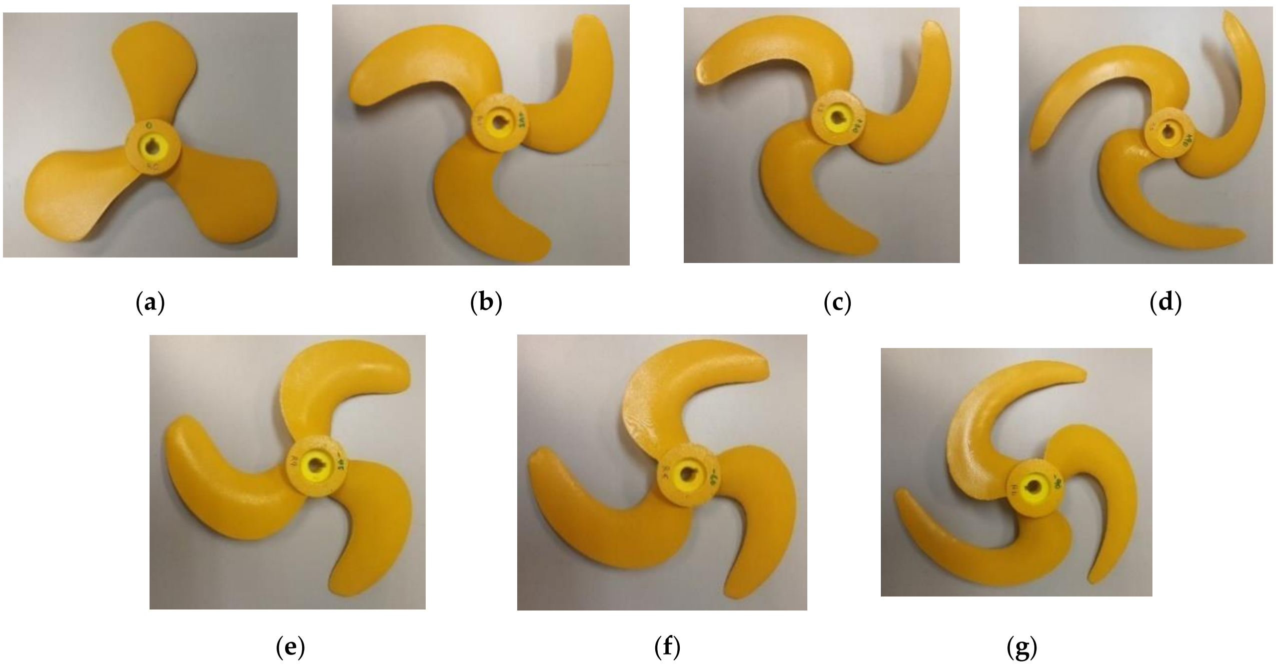

Figure 2. Turbine Rotor Model. (**a**) R0 Model. (**b**) R1 Model—+45° Skew. (**c**) R2 Model—+60° Skew. (**d**) R3 Model—+90° Skew. (**e**) R4 Model—−45° Skew. (**f**) R5 Model—−60° Skew. (**g**) R6 Model—−90° Skew.

Table 2. Planform and sectional offset of rotor with 0 skew (R0).

Radius	Chrdling	Pitch	Skew	Rake
0.20000	0.187711	0.51000	0.00000	0.00000
0.30000	0.192375	0.51000	0.00000	0.00000
0.40000	0.210398	0.51000	0.00000	0.00000
0.50000	0.253048	0.51000	0.00000	0.00000
0.60000	0.304159	0.51000	0.00000	0.00000
0.70000	0.349405	0.51000	0.00000	0.00000
0.80000	0.351700	0.51000	0.00000	0.00000
0.90000	0.282757	0.51000	0.00000	0.00000
0.95000	0.202396	0.51000	0.00000	0.00000
0.97500	0.131144	0.51000	0.00000	0.00000
1.00000	0.048819	0.51000	0.00000	0.00000

Table 3. Dimensions of the modifications made.

Dimension	Value (mm)
Thickness of hub	38.491
Soft hole radius	16
Diameter of hub	59.939
Rotor diameter	300 (±1)
Chamfer length of shaft hole and keyway	1
Chamfer length of recess	1

Figure 3. Dimensions of the HATT rig shaft.

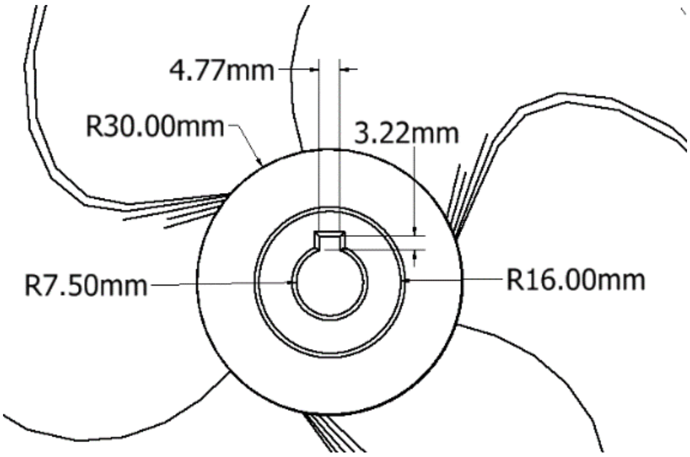

Figure 4. Dimensions of the rotor hub.

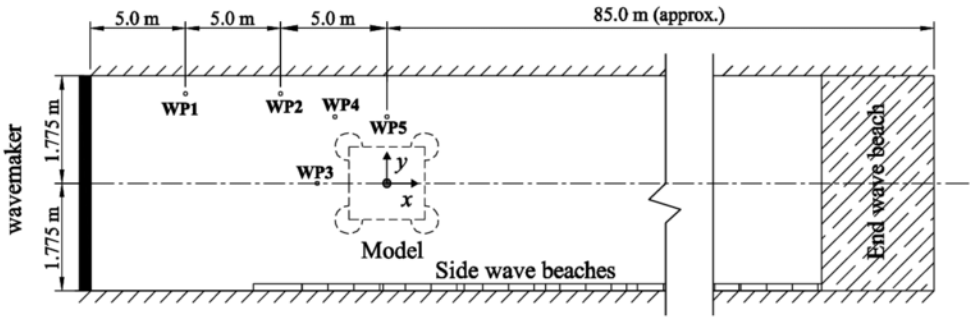

Figure 5. Top view of the towing tank at AMC.

2.2. Experiment Equipment and Apparatus

2.2.1. Towing Tank

The testing of the turbine rotor was conducted at the AMC Towing Tank facility using the HATT rig. The results were recorded and analyzed after the testing. The AMC Towing Tank was 100 m long and 3.5 m wide with a water depth of 1.48 m. The towing tank had a maximum carriage speed of 4.6 m/s. Figures 5–7 below show that the top view of the towing tank arrangement, the picture of the layout of towing tank and the carriage and the picture of the rotor installed on the testing rig with a rotor being installed under water.

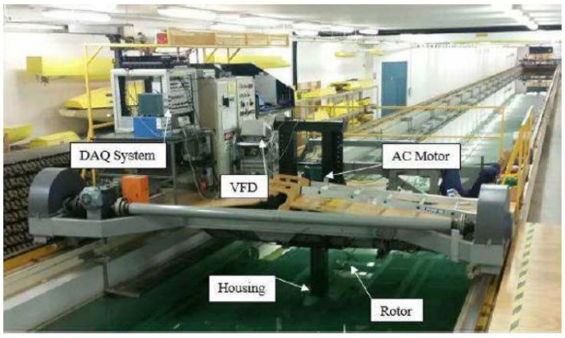

Figure 6. General setup.

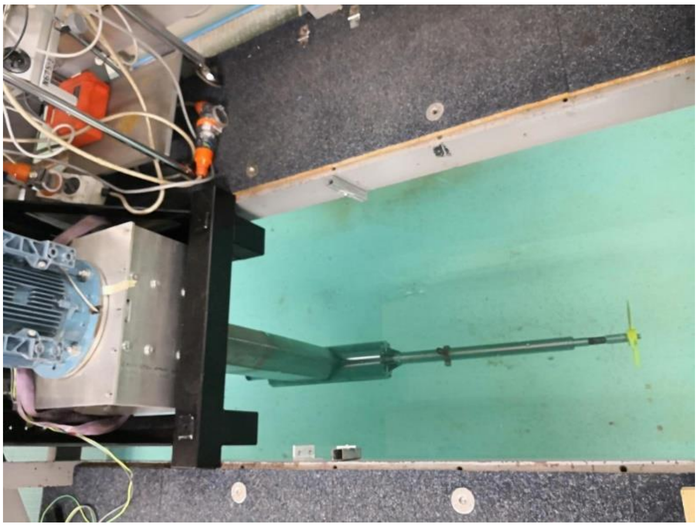

Figure 7. Underwater view of rotor setup.

The equipment used on the rig at the AMC Towing Tank facility and purposes (Table 4).

Table 4. Equipment and purposes.

Equipment	Purpose
90° Gear box	To convert the axis of rotation from the vertical shaft
Amplifier	To amplify the data collected from the strain gauge
Signal conditioner	To minimize the noise generated during signal capturing
AMCI Dura Coder analog encoder	To track the blade position and rotation speed of the rotor
QT255 Marine Tech Dynamometer	To measure the torque and thrust generated by the turbine rotor; it can measure torque up to 55 Nm and thrust up to 2200 N
AC motor	To rotate the rotor
Variable frequency drive (VFD)	To control the rotation speed of the AC motor, taking into account the speed of the carriage

2.2.2. 3D Printer

The 3D printer used to print the turbine rotors was a Creality CR-10S printer, as shown in Figures 8 and 9. Creality CD-10S is a fused deposition modeling (FDM)-type printer utilizing single-extruder technology. This printer can print at 0.1–0.4 mm layer resolution with a printing speed of 80–200 mm/s. Common 3D printing materials, such as PLA, ABS, PETG, TPU and special filaments, are supported by this 3D printer. This 3D printer has a maximum operational extruder temperature of 270 degrees Celsius.

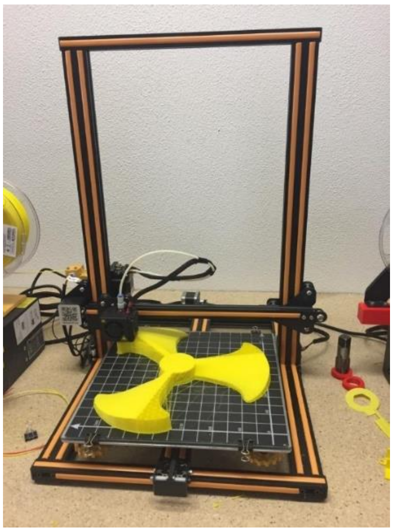

Figure 8. Creality CR-10S 3D printer printing platform.

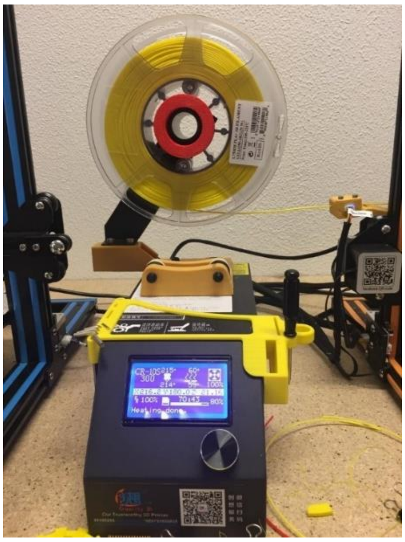

Figure 9. Creality CR-10S printer.

2.2.3. Calibration

Calibration was conducted to ensure the accuracy of the instruments and to process the data to obtain the actual values for thrust and torque. Thus, the calibration process was divided into two sections, thrust calibration and torque calibration. Thrust calibration was conducted by angling the HATT rig shaft upwards and applying force by adding weights, as shown in Figure 10. A linear graph was obtained to ensure the thrust sensor was calibrated. On the other hand, torque calibration was conducted by laying the HATT rig shaft down horizontally and applying force on each side (clockwise and counterclockwise), as shown in Figure 11. For torque calibration, an inclinometer was used to ensure both sides were level before the sensor was used to measure the torque. Figures 12 and 13 show the linear graphs that indicated the drag and torque sensors were calibrated. Gain and filter were set to enhance the sensor sensitivity and filter the noise generated. For torque, it was set to a negative calibration factor to obtain a positive value.

Figure 10. Thrust calibration test.

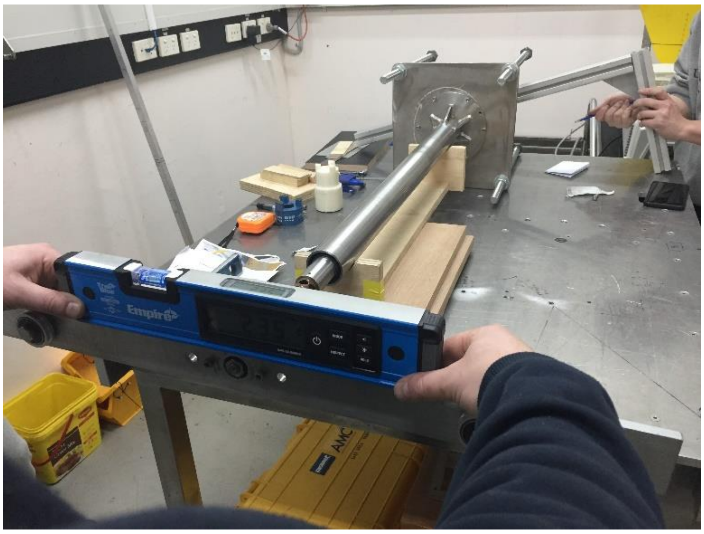

Figure 11. Torque calibration test.

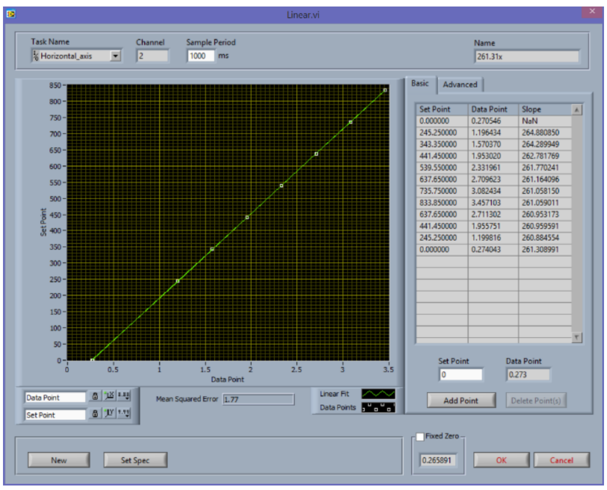

Figure 12. Thrust calibration graph.

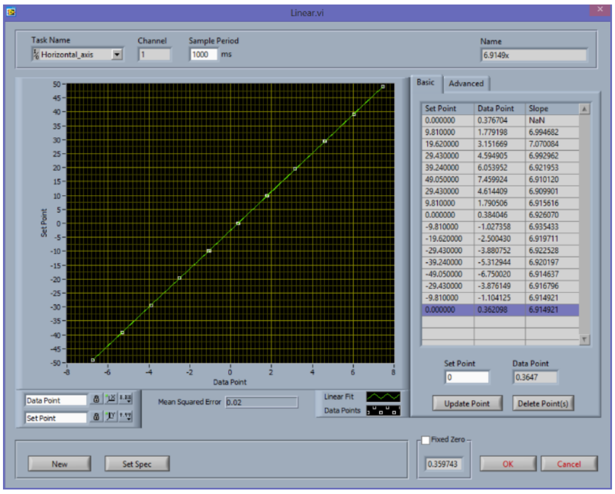

Figure 13. Torque calibration graph.

3. Results and Discussion

Torque K_Q and K_T thrust coefficient values were obtained throughout the experiment in amp value and converted into Nm and N, respectively. In order to obtain the torque and thrust coefficient, the following formulas were used:

$$K_Q = \frac{Q}{\rho n^2 D^5} \tag{1}$$

$$K_T = \frac{T}{\rho n^2 D^4} \tag{2}$$

where the density of water ρ is assumed to be 997 kg/m^3. The horizontal axis rotor swept area A is the plane of fluid flow on the bade, which can be written as:

$$A = \pi R^2 = 0.0707 m^2 \tag{3}$$

Tip speed ratio, TSR, is the ratio between the tangential speed of the tip of the rotor in terms of the actual speed of the fluid. The TSR is related to efficiency, with the optimum value varying with the blade design.

$$R = \frac{\omega R}{V_{in}} \tag{4}$$

3.1. Test Matrix for Data Acquisition

Testing was conducted at the Australian Maritime College (AMC) Towing Tank facility. The table below indicates the run matrix used for conducting the experiment.

In Table 5, J is the advance coefficient defined in the classical propulsion hydrodynamics, and the TSR, the tip speed ratio, was obtained by using the expression of the corresponding value. Re is the Reynolds number as defined by classic fluid dynamics, and RPM stands for revolution per minute. Elsewhere in the text, rps, in lower case, is used for revolution per second.

Table 5. Testing plan to prepare for the test run matrix.

Skew Angle (Degree)	Run No.	J	Re/10^6	TSR	Tow Speed (m/s)	RPM
7 rotors with high skew (−90/−60/−45/0/+45/+60/+90)	1	0.7306	11.1712	4.3	1.7534	480
	2	0.7854	11.1916	4	1.885	480
	3	0.8607	11.2219	3.65	2.0657	480
	4	0.9520	11.2623	3.3	2.2848	420
	5 *	1.0472	11.3086	3	2.5133	420
	6	1.1855	11.3833	2.65	2.8452	360
	7	1.3659	11.4937	2.3	3.2782	300

* An additional two runs were conducted for each rotor with the same TSR and tow speed, and the same amount of time to allow the water to return to a calm state.

Seven different skew angles for three turbine rotors were used, and each rotor was tested seven times with a different TSR and towing speed. Therefore, a total of 49 runs were conducted for the whole experiment, and an extra run was conducted if necessary (due to data error, data corruption). After each run was conducted, the water in the towing tank was allowed to return to its calm state before conducting the next run. An additional two runs were conducted to allow uncertainty analysis for one of the rotors at the same TSR and towing speed. By doing so, an average value and error were obtained. The TSR was set between 2.3 and 4.3 as the maximum power coefficient was estimated to fall between these values. The towing speed was restricted to below 3.5 m/s even though, as mentioned earlier, the maximum speed was set to 4.6 m/s due to safety issues. The RPM was set according to the restricted towing speed and to achieve the desired TSR.

3.2. Uncertainty Analysis

Measurements cannot be performed with perfect accuracy, and error cannot be avoided; however, it can be minimized. An uncertainty analysis was conducted based on the Taylor series method and in accordance with ITTC [14]. The precision and bias uncertainty were defined for all instruments, such as carriage speed, motor rpm, torque and thrust. The uncertainty in the measured values was then propagated to determine the uncertainty in the calculated variables, such as the thrust coefficient and torque coefficient. The standard error in each measured variable was estimated from a total of three runs including two repeated runs for each rotor at the same carriage speed. The equation below was used to calculate the uncertainty of the data:

$$E_r = \frac{E_a}{X_T} = \frac{\lceil X - X_T \rceil}{X_T} \quad (5)$$

where E_r is the relative error, E_a is the absolute error and X_T is the real value. The table below shows the maximum relative error percentage of all rotors. Tables 6 and 7 list the results of uncertainty analysis for the power and drag coefficients and carriage speeds.

Table 6. Uncertainty analysis of all rotors.

Rotor	Maximum C_P Error Percentage (±%)	Maximum K_T Error Percentage (±%)
R0	0.35%	0.23%
R1	0.59%	0.18%
R2	0.44%	0.42%
R3	0.31%	0.21%
R4	1.06%	0.53%
R5	0.27%	0.22%
R6	0.07%	0.42%

Table 7. Carriage speed and actual speed comparison.

Carriage Speed Set (m/s)	Actual Speed (m/s)	Error Percentage (±%)
2.0489	2.0444	0.44%
2.1339	2.1247	0.92%
2.1991	2.1945	0.49%
1.9992	1.9943	0.48%
2.0657	2.0646	0.10%
1.8850	1.8738	0.06%
1.7534	1.7443	0.91%

As shown above, the errors were relatively small as the maximum error percentage was 1.06% and the minimum error percentage was 0.07%. The carriage speed set and the actual speed of the carriage are shown in the table below with a maximum error of 0.91% and a minimum error of 0.06%.

3.3. Using Tare Thrust and Torque to Adjust Measurements

According to Liu et al. [13], the accuracy of torque measurements is much more important than drag/thrust for turbine rotor performance evaluation. A tare run was conducted to verify and obtain for data correction/adjustment. The AMC Towing Tank was designed to keep the environmental conditions constant before the experiment and after the experiment; thus, a tare run was only conducted for one day. No dummy hub was used to replace the rotor. Tare torque measurement runs were conducted with various RPMs corresponding to the inflow speeds, as previously mentioned, in the test matrix. The final torque and thrust can be calculated using the equation below:

$$Q_{final} = Q_{measured} \pm Q_{Tare} \quad (6)$$

Figure 14 shows the tare values at different tip speed ratio TSR.

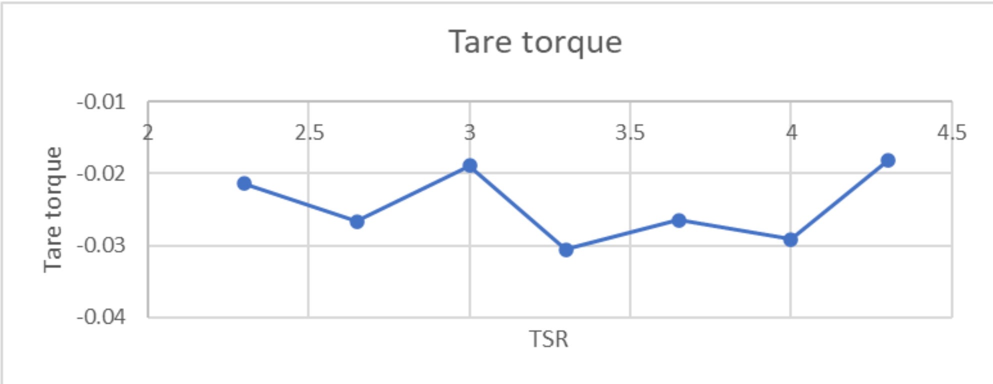

Figure 14. Tare torque vs. TSR.

3.4. Effect of Highly Skewed Turbine Rotor

For the results to be obtained, a negative skew was considered, and hence another three negatively skewed turbine rotors were added; that is, the skew was extended in the upstream direction. The extreme skew angle used for both the negative and positive directions was 90 degrees, which is the maximum practical skew angle a rotor blade could have.

Due to resource limitations and the need to strike a balance between resource use and testing various blade skew angles, the skew interval was set at 15 degrees starting from 45 degrees up to the extreme of 90 degrees.

As shown in Figure 15, the non-skewed rotor had the highest power coefficient among all the skewed rotors with a maximum power coefficient of 0.3558 at a TSR of 2.65. The power coefficient was reduced at a higher skew. The rotor with a negative 90-degree skew had the lowest maximum power coefficient of 0.244 at a TSR of 3.3. The rotors with a positive 45-degree and a negative 45-degree skew reached the maximum power coefficient at the same TSR of 3. At skewed angles of 60 and 90 degrees, negatively skewed rotors reached the maximum power coefficient at a higher TSR. Positively skewed rotors had a higher maximum power coefficient at a lower TSR than negatively skewed rotors. The table below shows the maximum power coefficient at the corresponding TSR of each rotor.

In terms of the efficiency of the skewed turbine rotors, according to Table 8, R3 and R6 (positive and negative 90-degree skew angles) had the highest power loss percentage compared to the maximum power coefficient with R0 and R3 and R4 (positive 60-degree and negative 45-degree skew angles), which had approximately the same power loss percentage, and finally, R2 (positive 45-degree skew angle) had the lowest power loss percentage. Positively skewed turbine rotors had less power loss than negatively skewed turbine rotors at the same skew angle. According to Mohammad A. Feizi Chekab et al. [15], by increasing the skew angle from 12 to 40 degrees, a 48% noise reduction can be obtained. Additionally, Mosaad et al. [8] stated that the main excitation source of vibration-related problems is pressure fluctuations, and skew has a beneficial effect on reducing pressure fluctuation and blade hydrodynamic unloading. However, increasing the skew angle will not always reduce the vibratory force as excessive skew can result in higher hydrodynamic loading on the propeller blades with negative pressure near the tip regions, as mentioned in the Introduction. Cavitation may occur in the turbine rotor, and increasing the skew angle may generate cavitation in the reloaded rotor blade elements. Therefore, rotors with a skew angle smaller than 60 degrees are the best design choice, minimizing the loss of power while also reducing noise and vibration, and thus being environmentally friendlier.

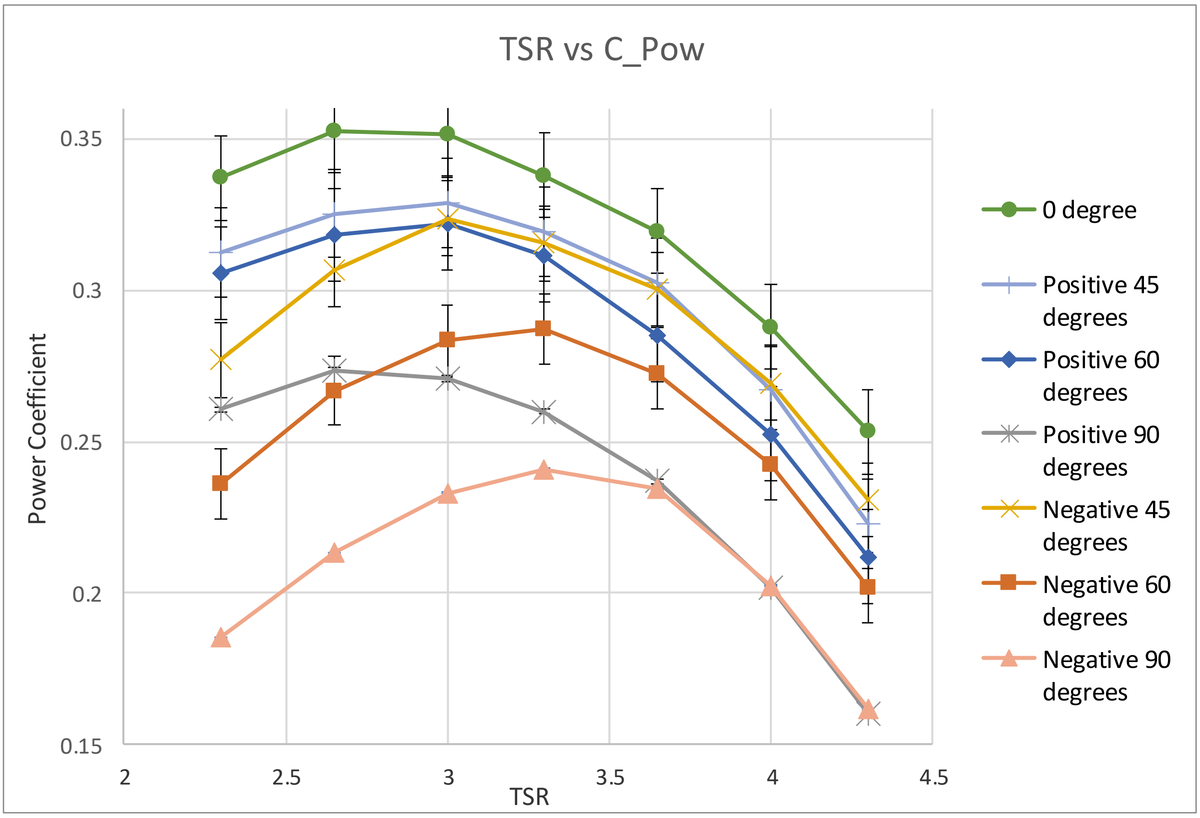

Figure 15. Tip speed ratio vs. power coefficient curve.

Table 8. Maximum power coefficient at the corresponding TSR of each rotor and the efficiency compared with R0.

Rotor	Power Coefficient Max	TSR	Power Loss
R0	0.3558	2.65	0.00%
R1	0.3310	3	−6.97%
R2	0.3251	3	−8.63%
R3	0.2766	2.65	−22.26%
R4	0.3268	3	−8.15%
R5	0.2921	3.3	−17.90%
R6	0.2440	3.3	−31.42%

The maximum power generation, i.e., the maxima of the Cpow, differed for the different skew angles, as detailed in the following:

- While zero skew produced the highest power generation efficiency Cpow, its maximum was at about TSR = 2.7.
- The efficiency loss is proportional to the increase in the blade skew, and the Cpow maximum gradually shifts to a higher TSR, with the greatest power efficiency loss for the negatively skewed blade seen at a TSR of about 3.3.

- The general trend of the skew effect on efficiency loss for positively skewed rotors was quicker than that of negatively skewed rotors.
- All of the positively skewed rotors had better power generation efficiency than the negative-skewed rotors with the same absolute skew angle.
- The positively skewed rotors had much higher power efficiency at a low TSR than the negatively skewed rotors.
- At a very high TSR, the power generation efficiency of the positively skewed rotors was about the same as that of the negatively skewed rotors.

The thrust coefficient of all the rotors can be seen in Figure 16. The thrust coefficient is known as the drag coefficient for turbine rotors. The drag/thrust coefficient is not directly related to hydrodynamic efficiency, but shows the extent to which the turbine affects the fluid flow. As shown, the drag coefficient constantly decreased as the TSR increased. In comparing the power coefficient and thrust coefficient, the positive-45-degree-skewed rotor (R2) could be seen to have the highest drag coefficient; however, it had a lower power coefficient than the 0-degree-skewed rotor (R0). Rotors with less skew had a higher drag coefficient and higher power coefficient.

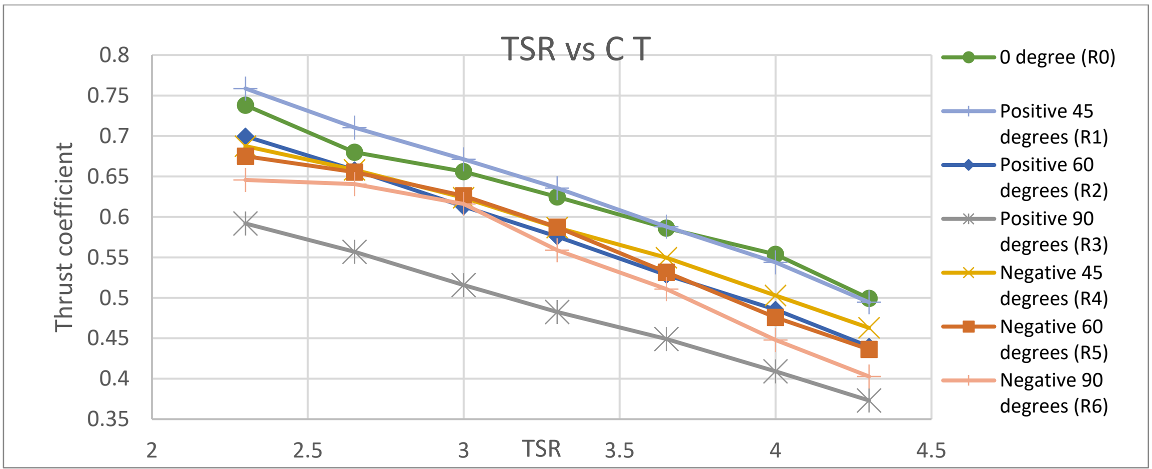

Figure 16. Thrust coefficient at different TSRs.

4. Conclusions

Renewable energy is the best option for the transition from non-renewable energy to a more environmentally friendly alternative. Therefore, when developing renewable energy operations, their environmental impact must be considered alongside the energy output to attract developers and investors. Several studies on tidal turbines have been conducted and published; however, an insufficient number of studies are available in terms of highly skewed turbine rotors. Thus, this research will be beneficial for future developments or improvements in the field. The experiment consisted of testing seven rotors, including one non-skewed rotor and six positively and negatively skewed rotors, and it was conducted in the AMC Towing Tank. The hydrodynamic performances of the seven rotors were then evaluated and compared. The testing facility kept the testing environment constant before and after testing to ensure the environment did not significantly affect the experiment results. Due to the relatively small size of the rotor tested, gain and filter were used to boost the signal from the dynamometer.

Several general trends of the skew effect on power efficiency were found, as follows:

- While zero skew produced the highest power generation efficiency Cpow, its maximum was at about TSR = 2.7.
- The efficiency loss is proportional to the increase in the blade skew, and the Cpow maxima gradually shifts to a higher TSR, with the greatest power efficiency loss for the negatively skewed blade seen at a TSR of about 3.3.

- The general trend of the skew effect on efficiency loss for the positively skewed rotor was quicker than that for the negatively skewed rotor.
- All of the positively skewed rotors had better power generation efficiency than the negatively skewed rotor with the same absolute skew angle.
- The positively skewed rotors had a much higher power efficiency at the low TSR than the negatively skewed rotors.
- At a very high TSR, the power generation efficiency of the positively skewed rotors was about the same as that of the negatively skewed rotors.

In addition, for all the skewed blades, a positive 45-degree skew led to the highest power coefficient and drag coefficient among all the skewed rotors and a negative 90-degree skew resulted in the lowest power coefficient, but a positive 90-degree skew led to the lowest drag coefficient. Under different circumstances, rotors with skew angles smaller than 60 degrees are more suitable for tidal turbines as they are able to minimize noise and vibration without losing too much power.

The 3D-printed materials were not quite rigid, so the results obtained might be slightly different from those obtained for metal turbine rotors with slightly higher power efficiency, but the trend of the skew effect on efficiency should be roughly the same. Cavitation, if there is any, might contribute substantial noise and vibration, but firsthand testing data on this aspect could be obtained at the towing tank. Obtaining detailed flow measurements would be ideal. These were the key limitations of the current study.

Regardless of the abovementioned limitations, this study found the correlation between the skew effect and power generation efficiency, and hence, provides a useful reference and firsthand experimental data for turbine designers and researchers in turbine research and design. The results could be very useful for the validation of numerical codes and CFD tools. The results and conclusion are also a valuable reference for the owners of the power generators.

Future work could be conducted using much more rigid metal rotors, testing the rotors in a cavitation tunnel to obtain their cavitation characteristics. Detailed flow measurements could be obtained by using the LDA and PIV equipment at a towing tank or a cavitation tunnel. Numerical studies using CFD are also encouraged to investigate the pressure gradient on the rotor's blade and visualize the flow behind the rotors to obtain the optimum field arrangement or to investigate the wake structure behind highly skewed turbine rotors.

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