Torque ripple and variable blade force: A comparison of Darrieus and Gorlov-type turbines for tidal stream energy conversion.

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Abstract

There are two main types of lift driven vertical axis turbine which can be used for capturing energy from tidal streams. These are the straight bladed ”Darrieus-type” and the helically shaped ”Gorlov-type”. The Darrieus-type turbine can suffer from vibrations in the shaft due to torque variations, known as ”torque ripple”. Gorlov-type turbines ought to reduce this problem but suffer from variations in force distribution along the length of turbine blade. The double multiple streamtube model (a blade element momentum model), with the Gormont-Berg adaptation for dynamic stall, is used to analyse the blade forces and shaft torques. The results show the extent to which torque ripple or variable blade force is effected by various other design choices, such as blade thickness, blade camber or turbine solidity. From these some of the requisite turbine characteristics are derived.

Keywords: Tidal Streams, Darrieus Turbine, Gorlov Turbine, Torque Ripple, Variable Blade Force

Nomenclature

Re = Reynolds number
α = blade angle of attack
θ = blade azimuthal angle
N = number of blades
c = blade chord length
r = turbine radius
U_∞ = freestream water velocity
ω = rotational speed
λ = tip speed ratio
ψ = turbine solidity
F = force
C = dimensionless coefficient
Q = torque
P = pressure
VR = variable defined in Eqn. 2, representing blade force variations

Subscripts

l = lift
d = drag
T = tangential
N = normal
p = performance
max = maximum value
min = minimum value
$ripple$ = ripple
var = variation

1 Introduction

The UK commands a potentially very large tidal stream energy resource. It is conservatively estimated to be 18TWh/year technically extractable [1] although this may occur to be a considerable underestimation [2]. Vertical axis turbines are a means of extracting the energy of tidal streams which are both multidirectional and well suited to shallow waters and low flow speeds. The turbines can be driven by either the lift or the drag acting upon the turbine blades. As drag based turbines are generally inefficient this paper will restrict itself to lift based turbines.

There are two basic forms a lift based turbine can take, the Darrieus turbine [3] or the Gorlov turbine [4]. Darrieus turbines can take a variety of forms, but are all characterised by all points on each blade having the same azimuthal angle, θ, at any time. Since the hydrodynamic forces acting upon the blade are a function of blade angle of attack, α, (which is a function of θ) the blade forces

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vary with time as the blades rotate. This in turn means that the shaft torque will fluctuate over time, known as torque ripple, which can cause vibrations in the shaft and potentially damage the turbine.

The Gorlov turbine has helically shaped blades. This means that at any point in time each possible value of θ is covered by a section of blade. This greatly reduces the torque ripple but will mean that each blade will cover all values of θ over a range of $\frac{2\pi}{N}$ and will thus be subject to variations in the bladewise force distribution.

This paper examines the impact of the turbine solidity ($\psi = \frac{Nc}{r}$) and different aspects of the turbine blade shape (thickness and camber) on the torque ripple of Darrieus turbines or blade force variations of Gorlov turbines. Another key aim is to maximise the power output, although this is beyond the scope of this particular project. Efforts have been taken, however, to ensure that all variable combinations considered provide similar power outputs. Wherever power is referred to in this paper it is as the performance coefficient, C_p, which is the rotor power as a percentage of the overall power available from kinetic energy across the turbine area.

2 Methodology

The turbine analysis was carried out using the double multiple streamtube (DMS) method, which is a blade element momentum model devised by Paraschivoiu [5]. The DMS method involves discretising the turbine volume into a collection of streamtubes, with actuator discs at the upstream and downstream points where the blade paths intersect with each streamtube. The DMS code can be adapted to allow for dynamic stall, the Gormont method with Berg's adaptation, as described by Masson et al [6], is used here. The model was written in Matlab.

The DMS method was chosen as it has been demonstrated to have good correlation with experimental data on numerous occasions [5–7] when analysing Darrieus wind turbines. The fluid density and viscosity were altered to make the model suitable for a turbine deployed in water.

The DMS is applied to a Gorlov turbine by recognising that a two dimensional horizontal slice of either Gorlov or Darrieus turbine is identical, so a Gorlov turbine can essentially be viewed as a collection of small Darrieus turbines stacked with a slight increase in θ for each level. It should be noted that applying this method to Gorlov turbines has not been validated by experimental evidence and other factors, such as three-dimensional flow effects due to the helical shape of the turbine, could effect the Gorlov turbine's performance.

Key to the success of the DMS model are the section data for the blades (C_l and C_d), which allows calculation of the blade element forces. Due to the wide range of α required over many different Reynolds numbers for effective analysis of a turbine there is not a huge amount of suitable data available. Gretton and Bruce [8] reviewed the available and suitable data for a number of thick, symmetrical NACA 4-series blades and concluded that there were differences between the different data sets (particularly post stall) which could lead to discrepancies between the results provided by DMS analysis.

The data set which covers the largest number of blades, over the full range of α, for a suitable range of Reynolds numbers is that of Sheldahl and Klimas [9]. Gretton and Bruce cast some doubt upon the methods used to acquire this data, but assuming that the error is consistent for different blades it should be appropriate for the sake of comparison. The Sheldhal and Klimas data is a combination of physically obtained data and numerically synthesised data. The data set only covers symmetrical blades so in order to study the effect of camber new data sets were produced using Eppler's code, Profile [10], for low α and Sheldahl and Klimas's blade independent data for high α. This provides consistency with Sheldahl and Klimas, who also used Profile for their numerically synthesised data.

The relationships between data for different blades are the same at different Reynolds numbers and each blade has a similar reaction to a change in Reynolds number, therefore, Fig.2 and Fig.3 show the data for fixed Reynolds number and fixed blade profile to avoid confusion. Fig.4 shows the blade and Reynolds number independant data for more extreme angles of attack.

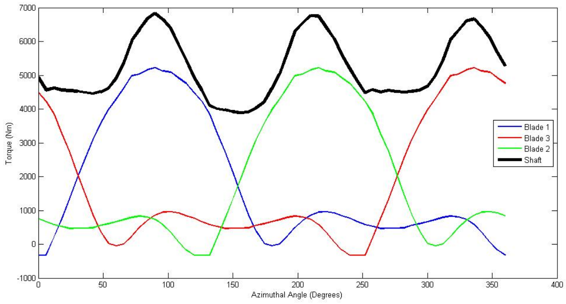
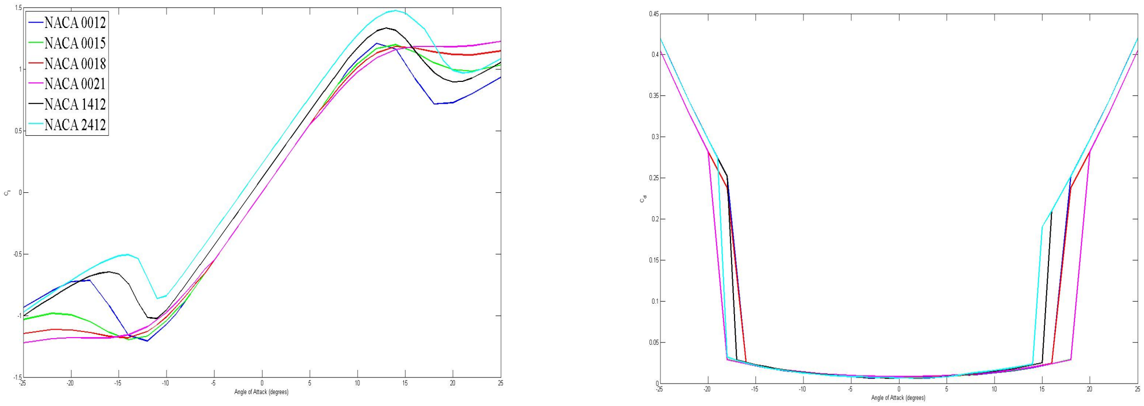


Figure 1: Darrieus Turbine: Blade and Shaft Torque Signals

For a Darrieus turbine, the torque ripple is calculated by simply by adding the blade torque signals to give the rotor torque, as shown in Fig. 1, then $Q_{ripple} = Q_{max} - Q_{min}$. For a Gorlov turbine, the blade force variations are slightly more complicated to calculate. For each level the pressure is given by:

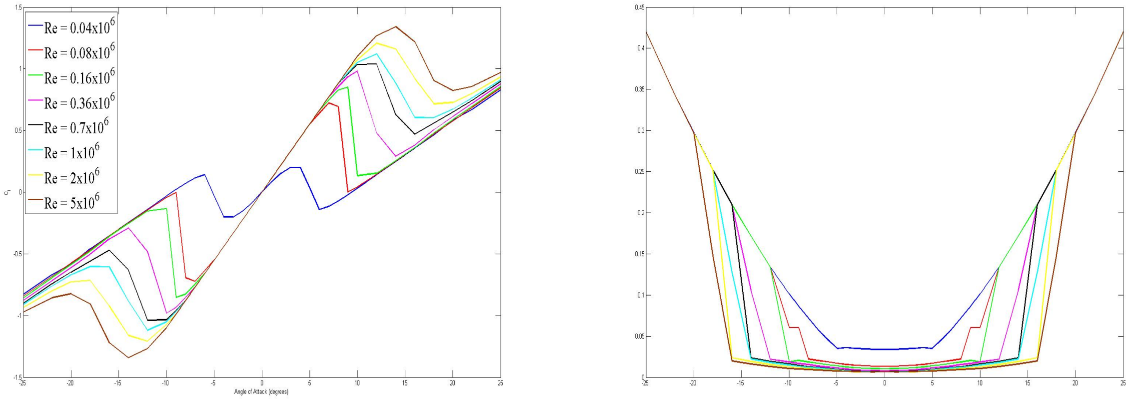
$$P = \frac{\sqrt{F_T^2 + F_N^2}}{c\Delta h} \tag{1}$$

One blade will experience the pressures for a range of $\frac{2\pi}{N}$, hence at any point in time there is a pressure variation of $P_{var} = P_{max} - P_{min}$ as demonstrated in Fig. 5. P_{var} will change as the blade rotates.



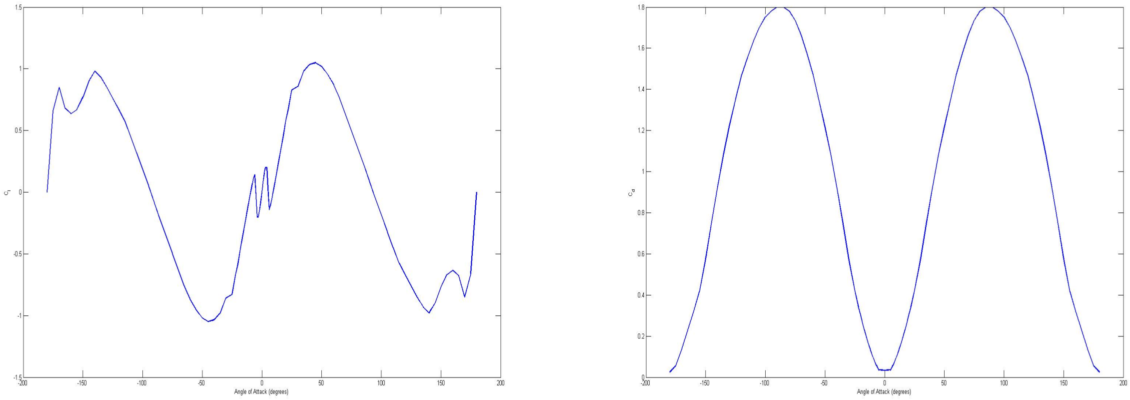
(a) C_l (b) C_d

Figure 2: Lift and Drag Curves for all Blades used at Re=2x10^6



(a) C_l (b) C_d

Figure 3: Lift and Drag Curves for NACA0012 over all Reynolds numbers



(a) C_l (b) C_d

Figure 4: Lift and Drag Curves for $0 \leq \alpha \leq 2\pi$

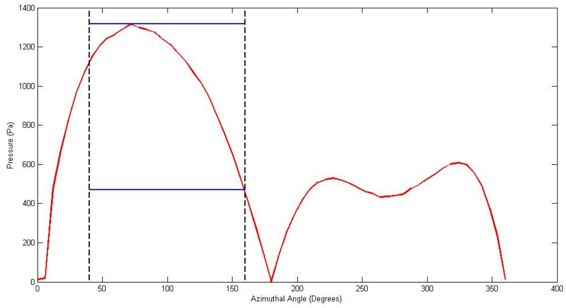


Figure 5: Pressure Changes During One Revolution

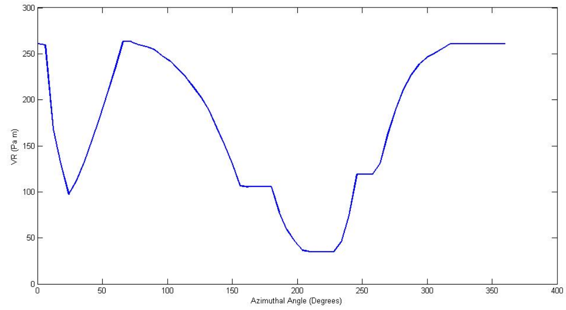


Figure 6: Gorlov Turbine: Evolution of VR

It should be noted that the blade with chord length of 0.1m has half the area of a blade with chord length 0.2m, therefore will be subjected to half the force when under the same pressure. Therefore in order to gain a picture of the blade force variation a new variable, VR, is defined as:

$$VR = cP_{var} \tag{2}$$

A typical evolution of VR is shown in Fig. 6, where θ is arbitrarily chosen as the θ value of the rear tip of the blade.

3 Set Up

The three variables to be analysed were turbine solidity, blade thickness and blade camber. The turbine height, turbine radius, number of blades and freestream water velocity were fixed. In order to alter solidity the blade chord length was altered. The turbines were analysed over a variety of tip speed ratios($\lambda = \frac{r\omega}{U_\infty}$), determined by varying the rotational speed. The dimensions were chosen to maintain the blade Reynolds number within the bounds of the Sheldahl and Klimas data (Re $\leq$ 5x10^6). It was decided to restrict the turbines to 3 blades for this paper to reduce complexity, it should be noted that both torque ripple and blade force variations will be greater for a turbine with less blades and reduced for a turbine with more blades. The values used are shown in Table 1.

Freestream Velocity	2ms^{-1}
Turbine Height	2.5m
Turbine Radius	2.5m
Rotational Speed (Tip Speed Ratio)	0.8rs^{-1} - 3.6rs-1 (1 - 4.5)
Chord Length (Solidity)	0.1m(0.12) 0.2m(0.24)
Blade Shapes (Thickness)	NACA0012 NACA0015 NACA0018 NACA0021
Blade Shapes (Camber)	NACA0012 NACA1412 NACA2412

Table 1: Turbine Variables

4 Results - Turbine Solidity

Increasing the solidity of a turbine will increase its power output at low tip speed ratios and decrease its power output at higher tip speed ratios. For a turbine with NACA0012 blades the peak performance is achieved for a turbine with tip speed ratio 4.5 for solidity 0.12 and tip speed ratio 3.5 for solidity 0.24. The rotor torque for each combination of these values can be seen in Fig. 7 and the torque ripple in Table 2.

Solidity	Tip Speed Ratio	C_p	Q_{Ripple}(Nm)
0.12	3.5	0.22	4623
0.12	4.5	0.29	1918
0.24	3.5	0.29	2937
0.24	4.5	0.22	1725

Table 2: Darrieus Turbine: Effect of Solidity on Torque Ripple

It is apparent that for both solidities there is a marked increase in the torque ripple for the lower tip speed ratio. There is also an increase in the torque ripple for lower solidities at fixed tip speed ratio, although this difference is less marked. Out of the two options giving peak power output, the combination of 0.12 solidity and 4.5 tip speed ratio has roughly only $\frac{2}{3}$ of the torque ripple of the other option, a difference caused mainly by the higher tip speed ratio. This would suggest that using a low solidity turbine at high tip speed ratio would be preferable. However, it should be noted that ψ can also be increased by adding blades (which is beyond the scope of this project), which may reduce Q_{ripple} by a greater extent (although possibly at the expense of power).

In the case of the Gorlov turbine the VR extent on one blade can be seen in Fig. 8 and the maximum VR values in Table. 3. These show a quite different pattern to Q_{ripple} for the Darrieus turbine. The decisive factor in the extent of VR is the solidity, with greater values for higher solidities regardless of the tip speed ratio. The reaction to changes in tip speed ratio is also different with

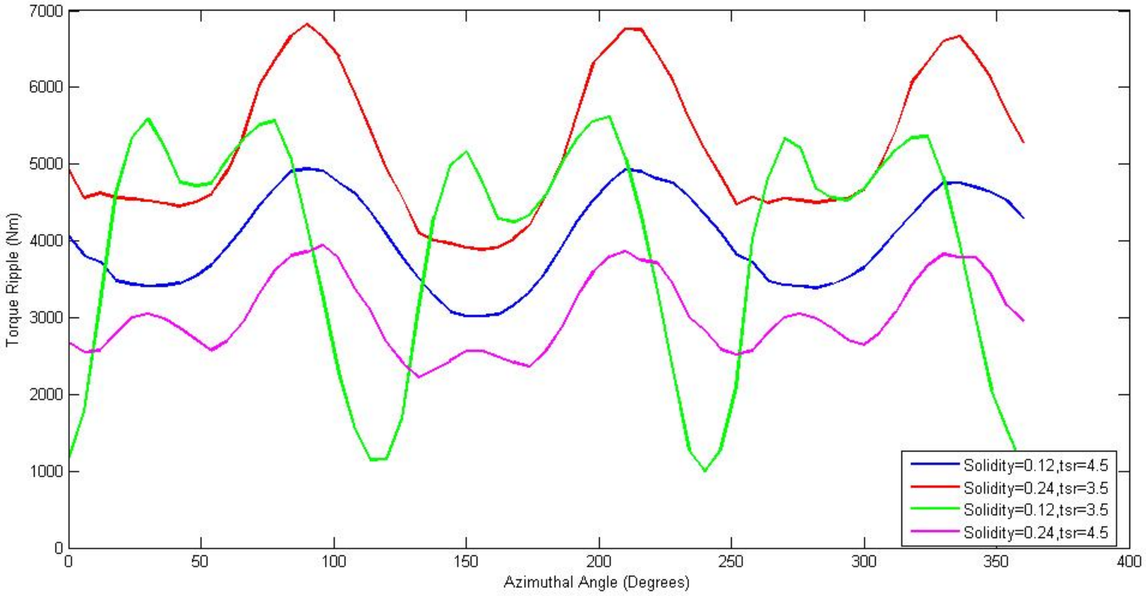


Figure 7: Darrieus Turbine: Shaft Torque for Varying λ and ψ

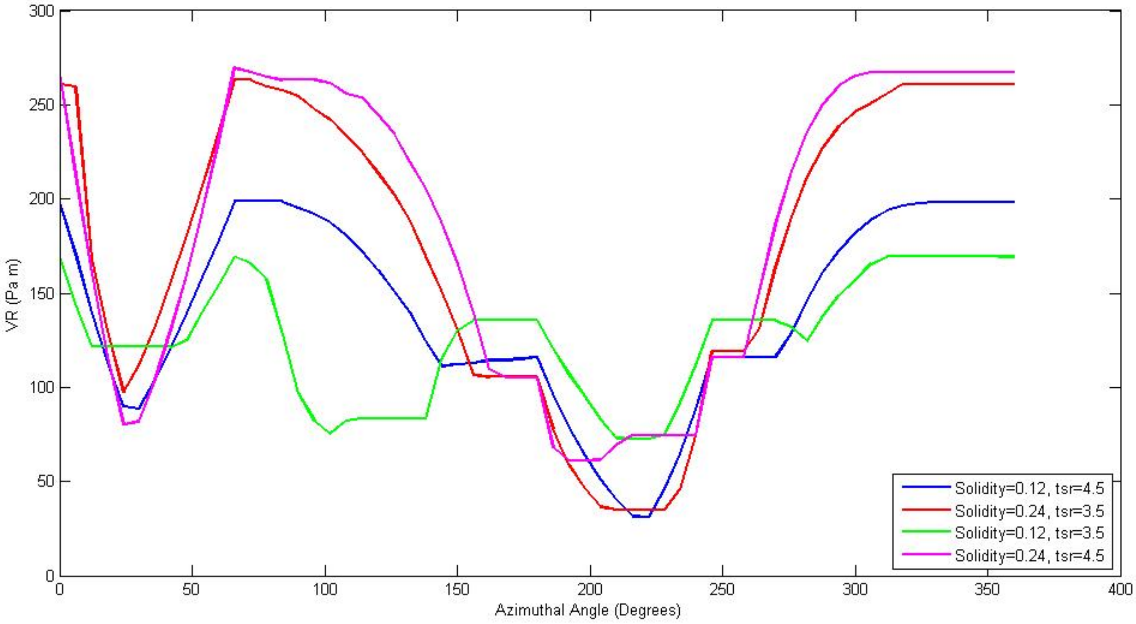


Figure 8: Gorlov Turbine: Variable Blade Force for Varying λ and ψ

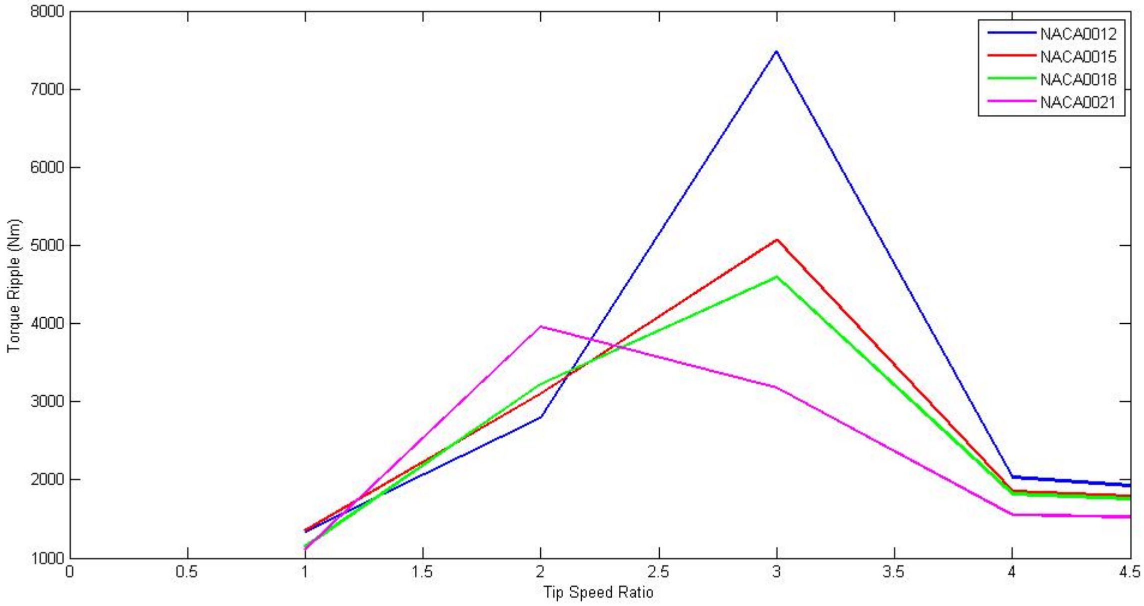


Figure 9: Darrieus Turbine: Effect of Blade Thickness on Torque Ripple

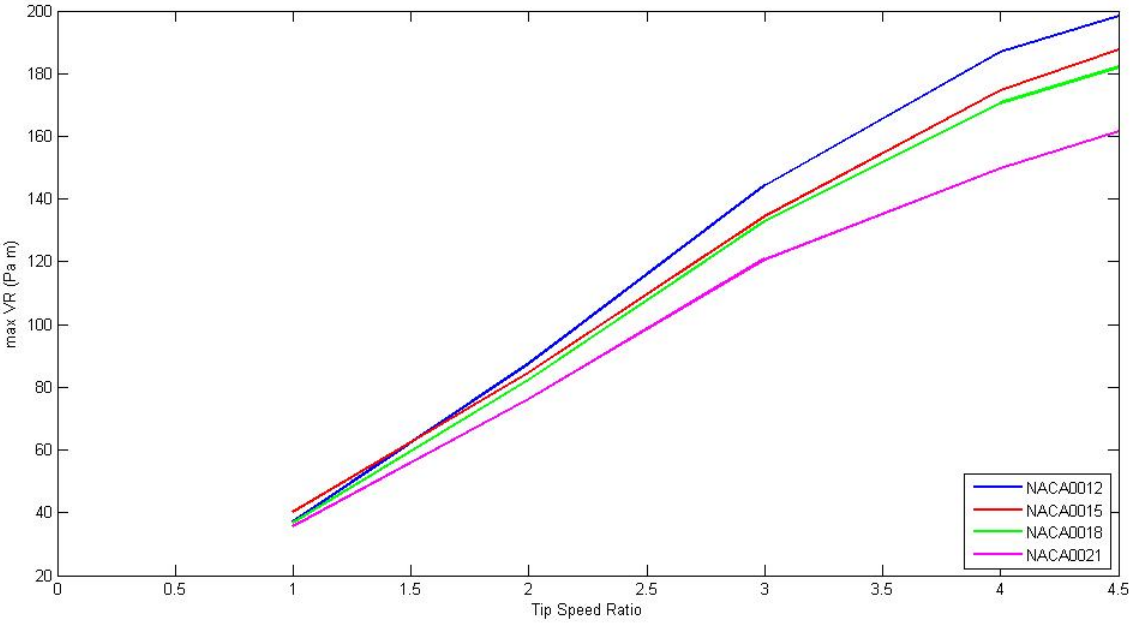


Figure 10: Gorlov Turbine: Effect of Blade Thickness on Maximum Blade Force Variations

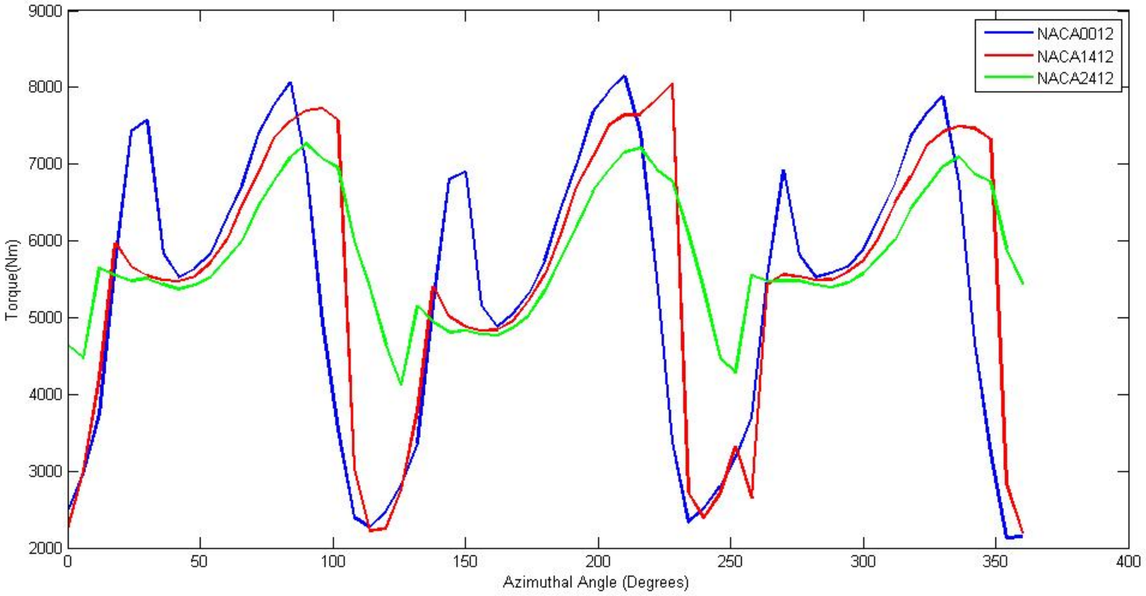


Figure 11: Darrieus Turbine: Effect of Different Cambered Blades on Shaft Torque

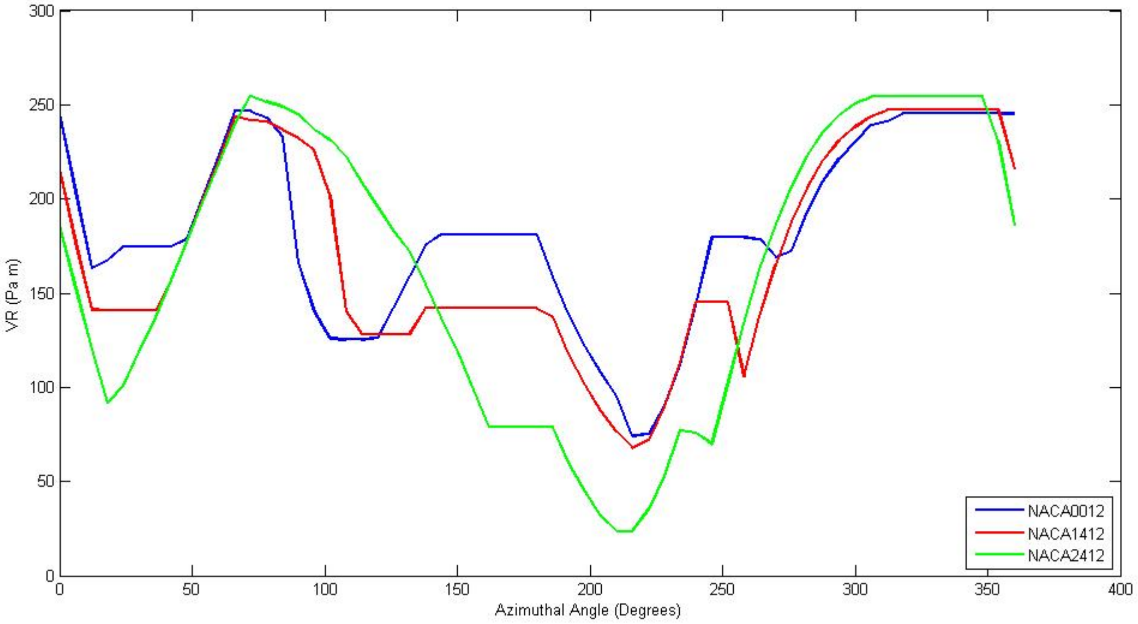


Figure 12: Gorlov Turbine: Effect of Different Cambered Blades on Variable Blade Force

VR increasing as tip speed ratio increases, although this is far less marked.

Solidity	Tip Speed Ratio	C_p	VR_{max}(Pa m)
0.12	3.5	0.22	169.4
0.12	4.5	0.29	198.5
0.24	3.5	0.29	263
0.24	4.5	0.22	269.4

Table 3: Gorlov Turbine: Effect of Solidity on Variable Blade Force

This would suggest that a lower solidity turbine is preferable. In order to maximise the power output this would suggest that a low solidity turbine operating at a high tip speed ratio is optimal, so despite the differences in the reaction of the torque ripple and variable blade force both can be minimised in Darrieus and Gorlov turbines by the same measures.

Despite this, however, there are other considerations which are in favour of higher solidity and lower tip speed ratio. Not only are higher solidity turbines likely to have better start up characteristics than low solidity turbines, but also being able to operate at full power on low tip speed ratio would potentially minimise problems such as disruption to the local environment or maintenance and make a turbine suitable for deployment in areas of low freestream velocity.

5 Results - Blade Thickness

For the four different thicknesses of blades there are not convenient values of λ which give the same power output as there were for the different solidities. Therefore it is necessary to seek potential compromises. To enable this plots of λ against C_p,Q_{ripple} and VR are presented in Fig. 13, Fig. 9 and Fig. 10.

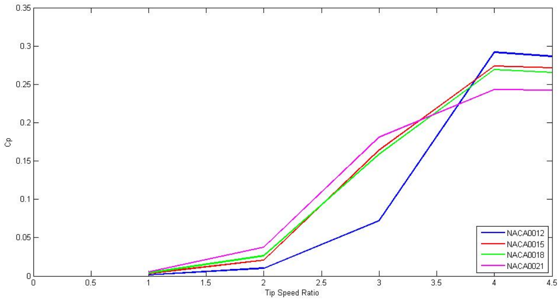


Figure 13: Turbine Power Output for Different Blade Thickness

Comparing Fig. 13 with Fig. 9 it is apparent that the curves for power and torque ripple both share certain characteristics, with thinner blades resulting both less power and less torque ripple at low tip speed ratios, and vice versa at high tip speed ratios. If the curves were the same shape this would suggest that the goal of high power output and low torque ripple are incompatible. However, the curves are differently shaped in parts, which suggests that meeting both objectives is not beyond possibility. For instance using the NACA0012 blade at λ=4 would provide a high power output with low torque ripple, although the thicker bladed turbines suffer from much less ripple at lower tip speed ratio (e.g. λ=3, which a turbine will have to pass through at start up and shut down) without sacrificing too great an amount of power.

The case for the Gorlov turbine is more straightforward. Fig. 10 shows that the maximum blade force variations are consistently higher for the thinner blade profiles. Given that a thicker blade ought to be more structurally robust as well, this suggests that the blades should be made as thick as possible (although not so thick that turbine power output is significantly compromised).

6 Results - Blade Camber

Although the fact that a blade has to operate for both positive and negative α makes it tempting to restrict analysis purely to symmetrical blades, it is possible that a cambered blade will compensate for its lack of performance for negative α by increased performance at positive α. For example, for λ=3, turbines using the NACA0012, NACA1412 and NACA2412 sections all have approximately the same power output. Fig. 14 shows that the torque signal for an individual blade is high for both upstream ($0 \leq \theta \leq \pi$) and downstream ($\pi \leq \theta \leq 2\pi$) regions for the NACA0012, and becomes greater upstream and lesser downstream (i.e. less even) for blades of greater camber. This could be taken to suggest that the torque ripple will be more pronounced for the higher camber blades.

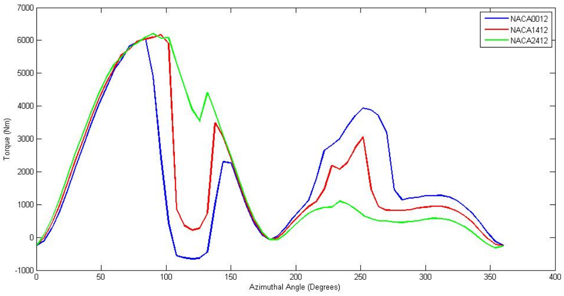


Figure 14: Individual Blade Torque Signals for Different Cambered Blades

Blade Profile	C_p	Q_{ripple}(Nm)
NACA0012	0.28	6014
NACA1412	0.26	5858
NACA2412	0.26	3148

Table 4: Darrieus Turbine: Effect of Blade Camber on Torque Ripple

However, Fig. 11 and Table 4 provide an unexpected result, with the NACA2412 turbine having only just over half the torque ripple of the NACA0012 turbine. This would appear to be down to the more favourable stall characteristics of the NACA2412 in the upstream section.

Blade Profile	C_p	VR_{max}(Pa m)
NACA0012	0.28	246.6
NACA1412	0.26	247.7
NACA2412	0.26	254.8

Table 5: Gorlov Turbine: Effect of Blade Camber on Variable Blade Force

For the Gorlov turbine, Table 5 shows that there is not a great deal of difference in the maximum variable force experienced by the blades of each turbine, but that the variation is slightly greater for more cambered blades. Fig. 12 shows that the less cambered blades are experiencing high values of VR for a greater proportion of the revolution. This is inconclusive and would suggest that blade camber is not vital in designing a Gorlov turbine with low blade force variations.

7 Conclusions

The variables examined above effect the torque ripple of a Darrieus turbine and the blade force variations of a Gorlov turbine differently. Work done to date would suggest that for a Darrieus turbine with low torque ripple a Darrieus turbine of low solidity and high tip speed ratio, designed with blades of some camber (2% of the chord length) and moderate thickness (12-18% of the chord length) would be optimal. Likewise for a Gorlov turbine low solidity and high tip speed ratio would be preferable but in this case thicker blades with less camber would produce less blade force variations. However, many other design considerations will also have an effect.

Given the great forces that any turbine will be under in the marine environment the variable blade force might well mean that a Gorlov turbine blade will require much stronger material than a Darrieus turbine blade. Combined with the more complicated nature of the blade's construction this could mark Gorlov turbines at a serious disadvantage. Darrieus turbines will require more robust shafts (and potentially moorings) than Gorlov turbines, but this ought to be a more straightforward problem to overcome.

It should be noted that this paper only provides a snapshot of the problem and that more extensive investigations are being undertaken, including examining the interactions between different variables and attempting the design of new blades, specific to these turbines.

Acknowledgements

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