Variable Pitch Darrieus Water Turbines*

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Abstract

In recent years the Darrieus wind turbine concept has been adapted for use in water, either as a hydrokinetic turbine converting the kinetic energy of a moving fluid in open flow like an underwater wind turbine, or in a low head or ducted arrangement where flow is confined, streamtube expansion is controlled and efficiency is not subject to the Betz limit. Conventional fixed pitch Darrieus turbines suffer from two drawbacks, (i) low starting torque and (ii) shaking due to cyclical variations in blade angle of attack. Ventilation and cavitation can also cause problems in water turbines when blade velocities are high. Shaking can be largely overcome by the use of helical blades, but these do not produce large starting torque. Variable pitch can produce high starting torque and high efficiency, and by suitable choice of pitch regime, shaking can be minimized but not entirely eliminated. Ventilation can be prevented by avoiding operation close to a free surface, and cavitation can be prevented by limiting blade velocities. This paper summarizes recent developments in Darrieus water turbines, some problems and some possible solutions.

Key words: Turbine, Hydrokinetic, Darrieus, Variable Pitch, Starting Torque, Shaking, Ventilation, Cavitation

Nomenclature

c	chord length (from leading edge to trailing edge of blade)
C_p	coefficient of performance (= power produced $\div$ kinetic energy flux intercepted)
C_Q	coefficient of torque (= C_p/λ)
n	number of blades
r	turbine radius
α	angle of attack
λ	tip speed ratio (ratio of blade velocity to ambient current velocity)
θ	circumferential position of blade relative to position where blade is travelling directly upstream ("azimuth angle" in vertical axis wind turbine terminology)
σ	solidity = nc/r

1. Introduction

The Darrieus vertical axis wind turbine concept attracted considerable research interest in the late 1970s and 1980s, but has never competed successfully with horizontal axis wind turbines. In recent years there has been growing interest in hydrokinetic turbines, i.e. water turbines which convert the kinetic energy of flowing water rather than relying on a "static head" or difference in pressure across the turbine. These may operate in river, tidal or marine current flows. Examples include MCT's axial flow turbine⁽¹⁾ shown in Fig.1, and variable pitch Darrieus designs such as the Italian Kobold turbine⁽²⁾ (Fig.2) and the large ring gear turbine concept of Salter and Taylor⁽³⁾. They are directly analogous to wind

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turbines in that the maximum energy they can capture in open flow is governed by the Betz limit, i.e. 59.3% of the kinetic energy in the intercepted flow for a single actuator disk (axial flow turbine) or 64% for a double actuator disk, i.e. cross flow turbine⁽⁴⁾, due to the divergence of the streamtubes in unconfined flow. However Salter and Taylor⁽³⁾ have argued that turbines in a densely packed array across a channel of limited cross sectional area are effectively in a partially confined flow, and higher efficiencies might be achievable. Unlike wind turbines, water turbines are also subject to ventilation and cavitation at high flow velocities, so blade tip speed ratios are limited.

Fig.1. MCT's axial flow tidal turbine.

Fig.2. Kobold cross flow turbine.

There is also interest in Darrieus-type turbines for ultra-low head confined flow applications, where flow is not able to go around the turbine. Examples include Blue Energy Canada Inc's Tidal Fence, Fig.3⁽⁵⁾, and the low head hydro concept of Furukawa and Okuma⁽⁶⁾, shown in Fig.4. In these designs streamtube expansion through the turbine can be prevented and energy is extracted from a pressure drop, as in conventional hydro and tidal barrage turbines, rather than from a reduction in flow velocity as in wind turbines. Thus they are not subject to the Betz limit and higher efficiencies can be achieved, but they require that the complete flow area be channeled through the turbine, which is not practicable in all situations.

Fig.3. Blue Energy's tidal fence.

Fig.4. Low head hydro (4).

Between the two extremes of open flow and fully confined flow, turbines can be placed inside a duct in open flow to create a small pressure drop across the turbine. The designs of Tidal Energy Pty Ltd⁽⁷⁾, (Fig.5), New Energy⁽⁸⁾ and Ponta and Dutt⁽⁹⁾ are examples of Darrieus turbines in a duct, while Clean Current⁽¹⁰⁾ have a ducted axial flow turbine (Fig.6). These all use a simple venturi type duct, except for the design of Tidal Energy Pty Ltd which uses a series of foil-shaped slats for boundary layer control to prevent flow separation in a short, wide angle diffuser. By suitable design of this duct, the power output

of a given turbine can be augmented by a factor of three⁽¹¹⁾.

Fig.5. Tidal Energy Pty. Ltd's slatted diffuser, raised partly out of the water.

Fig.6. Model of Clean Current's ducted axial flow turbine.

2. Darrieus water turbine problems

Cross flow Darrieus hydrokinetic turbines have some advantages over axial flow turbines. These include the following:

1. With axis oriented vertically they can directly drive a generator above water level.
2. In a tidal flow they are insensitive to changes in flow direction.
3. A row of turbines on a common horizontal shaft can sweep a wide, shallow channel and they do not need to yaw in a reversing tidal flow.
4. Blades are untwisted and of uniform cross section, so they can be extruded at low cost.

However they also have some problems. These are discussed below, and solutions are suggested.

2.1 Self-starting. Conventional fixed pitch Darrieus turbines, whether in wind or water, suffer from low or negative torque at low tip speed ratios as shown in Fig.7. This can prevent the turbine from accelerating up to operating speeds, a significant drawback at a tidal site where slack water normally occurs four times per day, twice at high tide and twice at low tide, and the turbine must start again as the flow velocity increases. If it does not start until the tide is running strongly, a lot of energy is lost.

Fig.7. Fixed pitch turbine torque characteristic showing low or negative torque at low tip speed ratios⁽¹²⁾.

2.2 Shaking. Unlike axial flow turbine blades, the blades of a fixed pitch Darrieus turbine are subjected to continuously changing angles of attack as the turbine rotates (Fig.8, left), which generate changing fluid dynamic forces (Fig.8, right), so the turbine tends to shake.

Fig.8. Left: angle of attack α , and right: tangential force F_T^* , as functions of circumferential position θ for tip speed ratios $\lambda = 2.0, 2.5$ and 3.0 , and turbine solidity $\sigma = 0.84$.

This can be a very serious problem if the frequency of shaking coincides with the resonant frequency of the support structure. Also it is potentially more of a problem in water than in air, due to the incompressibility of water. Darrieus wind turbines with two blades have been observed to shake alarmingly^{(13) (14)}, but the first author has tested several prototype Darrieus wind turbines with three variable pitch blades and has not experienced any problems with shaking. It was expected that the same would be true for water turbines with three or more blades, and two ducted variable pitch Darrieus water turbines tested by Tidal Energy Pty Ltd in Queensland, Australia in 2003 and 2005⁽¹¹⁾ experienced no obvious shaking problems. However these tests were done at ambient current velocities less than 0.7 m/s, so forces were small and shaking may have been present. A Darrieus water turbine with three fixed pitch straight blades (Fig.9) was tested in much more demanding conditions in currents up to 5 m/s by Coastal Hydropower Corporation in Canada in 2007⁽¹⁵⁾ and was found to vibrate or shake severely. This led to an examination of ways to prevent or minimize shaking.

Fig.9. Straight blade Darrieus (left) and Gorlov helical turbine (right).

Fig.10. Ventilation of a turbine blade.

2.3 Ventilation and Cavitation. These two terms are often confused. Ventilation is caused by sucking in air from a free surface, while cavitation is caused by vaporisation of water. Both are caused by reduced pressure due to local high water velocities, and both can adversely affect the performance of water turbines. Axial flow turbines can be designed for any desired tip speed ratio, so those designed for high current speeds can avoid excessive water speeds by using low tip speed ratios. But Darrieus turbines should operate at tip speed ratios high enough to avoid blade stall, which occurs when the angle of attack exceeds about 15° . Thus they should be designed to operate at $\lambda > 3$ (Fig.8, left). Fig 10 shows air bubbles apparently sucked in by low pressure around a turbine blade. In turbine tests conducted in Canada in 2007 by the first author in collaboration with Coastal Hydropower

Corporation, a serious loss of performance was observed at current velocities above about 4 m/s.

3. Possible solutions

Some possible solutions to the problems outlined above are discussed below.

3.1 Improving torque at low tip speed ratios

Various measures to improve low speed torque have been discussed in Refs ^{(16), (17)} in relation to wind turbines, and the same principles apply to water turbines. These include

1. Increased solidity. Fig.11 shows how the power output of a fixed pitch turbine with higher solidity is higher at low speeds, indicating higher torque. However it will also be seen from Fig.11 that efficiency suffers if the solidity is too high. This is a result of blade stall, since the tip speed ratio for optimum efficiency is lower, about 2.2 for the turbine with solidity $\sigma = nc/r = 0.84$. From Fig.8 (left) it will be apparent that fixed pitch blades will stall at this tip speed ratio.
2. Cambered blades can improve starting performance at low Reynolds numbers, but peak performance suffers, as shown in Fig.7⁽¹²⁾ ⁽¹⁸⁾.
3. Inclined blades. Baker⁽¹⁹⁾ has shown that inclined blades can improve starting performance because they stall less abruptly, but it appears that a large inclination of the order of 45° is necessary to ensure good starting, and this may not be practicable.
4. Helical blades, which are effectively inclined blades wrapped around the surface of an imaginary cylinder, may produce slightly higher starting torque than an equivalent straight blade Darrieus turbine due to (i) the evening out of torque fluctuations with θ , and (ii) less abrupt stall of inclined blades, as discussed by Baker. However starting torque will not be high unless variable pitch blades are used, and it is not possible to pitch helical blades.
5. Turbines connected to generators which can also operate as motors can be motored up to speed, so lack of low speed torque is not necessarily a serious problem, but the system design is simplified if the turbine will reliably self-start.
6. Variable pitch blades can produce high starting torque and low speed torque combined with high peak efficiency, as shown in Fig.12, in which " $\gamma = 0$ " denotes fixed pitch and the other three curves are for different pitch amplitude limits. Literature on variable pitch vertical axis wind turbines is summarized in Refs ^{(17), (20)}.

Fig.11. Predicted performance of 1m dia. Turbines with blade chord lengths of 0.1, 0.12 and 0.14 m, corresponding to solidity $nc/r = 0.6, 0.72$ and 0.84 .

Fig.12. Predicted torque-speed curves for fixed pitch and passive variable pitch turbines with different pitch amplitude limits.

3.2 Reducing or eliminating shaking

3.2.1 Helical blades. Coastal Hydropower Corporation tested a Gorlov Helical turbine with three blades, each covering 1/6 of a turn (Fig.9), using an identical test procedure to that used with the straight blade Darrieus. Its performance was similar to that of the Darrieus except that it did not shake noticeably, which is to be expected, since elements of each blade cover a range of circumferential positions at any given moment. If three blades each wrap around 1/3 of a turn, then the net force on the whole turbine will be essentially independent of circumferential position, although there will be some variation in force at each end.

3.2.2 Large number of straight, fixed pitch blades. In theory, the more blades there are, the more the fluctuations in resultant force on the turbine with circumferential position will average out. However more blades entail more fabrication and cost, and either higher solidity or smaller chord length. As observed above, performance suffers if solidity is too high, and small chord length means blades are less mechanically strong. Blade chord Reynolds number also decreases, with resulting decrease in performance of small turbines in slow flows.

3.2.3 Variable pitch regime. Variable pitch can produce large starting torque (Fig.12) and high efficiency, but shaking forces can be very high, as shown in Fig.13.

Fig.13. Tangential (left), and radial (right) forces on a single blade as functions of circumferential position θ . Fixed pitch shown dotted, full lines show various pitch regimes.

3.2.4 Parametric study to minimize shaking. In order to reduce these shaking forces, a parametric study was undertaken with the aim of minimizing shaking forces without significantly reducing performance. This work was initially based on a new passive pitch control mechanism which allows blades to pitch when the angle of attack reaches a desired limit. A cam-driven active pitch control system, which can produce any desired pitch regime and hence any desired angle of attack regime at a given tip speed ratio, was also studied. The pitch control mechanisms, methodology and findings of this study will be reported in more detail in a forthcoming paper, but a brief summary is given below. The procedure was:

- 3.2.4.1 Resolve blade force into either radial and tangential components or downstream and cross stream components.
- 3.2.4.2 Sum force components from all blades.
- 3.2.4.3 Define a shaking parameter, either maximum deviation from mean force or average deviation from mean force.
- 3.2.4.4 Multi-objective memetic algorithm to minimise shaking parameter without significantly reducing efficiency.
- 3.2.4.5 Examine plot of shaking force vs. circumferential position and identify changes to pitching regime to reduce peaks.

Fig.14 shows how shaking forces can be reduced substantially by suitable selection of pitch control regime.

Fig.14. Downstream shaking force for fixed pitch and various pitch control regimes.

Fig.15. Velocity contours around NACA 0018 profile for various α .

3.3 Avoiding cavitation and ventilation

Ventilation. As the water velocity increases, pressure energy is converted to kinetic energy, the pressure drops and the surface level also drops by an amount called the velocity head $V^2/2g$. If the flow velocity is uniform the surface remains flat, but if the local velocity is higher or lower, for example around a bridge pier, the local water level will be lower or higher than the surrounding level. Local high velocities occur where the fluid accelerates to get around the convex sides of hydrofoils (Fig.15), resulting in reduced pressure. Under certain conditions air may be sucked into the water (Fig.10). This can occur with boat propellers, upsetting the flow dynamics and reducing performance, and the same thing can happen with a hydrokinetic turbine at a shallow depth below a free surface.

Cavitation. Ventilation is prevented in the absence of a free surface, but cavitation will still occur if the local pressure falls below the vapour pressure of water. In this case pockets of water vapour form in low pressure regions, and these can not only upset the flow dynamics and performance as in the case of ventilation, but as the pressure varies with θ and α , they tend to implode and erode blade surfaces.

Example. Take for example a flow velocity of 3 m/s. The velocity head $V^2/2g = 3^2/(2 \times 9.8) = 0.46$ m. So the surface is 0.46 m lower than it would be if static. If a blade is travelling through the water at a tipspeed ratio of 4, the velocity will range from $3(4+1) = 15$ m/s when travelling directly upstream ($\theta = 0^\circ$), through a little over 12 m/s when travelling across the stream ($\theta = 90^\circ$), to $3(4-1) = 9$ m/s when travelling directly downstream ($\theta = 180^\circ$). But the local peak *relative* velocity between blade and water near the leading edge will be considerably higher, nearly twice as high for a NACA0018 profile when $\alpha = 8^\circ$ according to Fig.15, i.e. approximately 24 m/s when $\theta = 90^\circ$. Since the blade is travelling at 12 m/s, the *absolute* water velocity is at least 12 m/s, and the velocity head is approximately $V^2/2g = 12^2/(2 \times 9.8) = 7.35$ m. Thus the surface level above the leading edge of the blade will tend to drop by $(7.35 - 0.46) = 6.89$ m relative to the surrounding water. If the blade is submerged by less than 6.89 m below a free surface it will tend to ventilate by forming a vortex at this point, as shown in Fig.10. But it will not cavitate as it will still experience an absolute pressure equivalent to atmospheric less 6.89 m of water, i.e. about 0.3 bar, which is much higher than the vapour pressure of water at normal temperatures. This calculation

would have to be repeated for a range of current velocities, tip speed ratios and circumferential positions to fully assess the likelihood of ventilation or cavitation.

Thus ventilation can be avoided by placing a turbine under a solid surface rather than under a free surface. Ventilation and cavitation can be prevented by submerging the turbine well below the surface and/or keeping blade velocities reasonably low. Fixed pitch Darrieus turbines must maintain $\lambda > 3$ to avoid stall (Fig.8) so as to achieve good performance. Thus it is impossible for a fixed pitch turbine near the surface to achieve good performance in a high velocity current, since performance will be limited by stall at low λ and by ventilation and/or cavitation at high λ . However variable pitch can prevent stall at low λ and so avoid this dilemma.

Conclusion

Darrieus water turbines have applications at river and tidal sites, both in open flow and with low static head. They have some advantages over axial flow turbines: they can easily drive a generator above water level, they do not need to yaw in a reversing tidal flow, and blades are untwisted and of uniform cross section, so they can be extruded at low cost. However they also have some disadvantages, mainly related to self-starting, shaking and ventilation and cavitation. It is argued that helical turbines can eliminate shaking but fixed pitch turbines cannot produce high starting torque, nor can they achieve good performance in strong currents. However variable pitch turbines can produce high starting torque and high peak efficiency, and with suitable choice of pitch regime, shaking can be kept within acceptable limits.

References

- (1) Marine Current Turbines. <http://www.marineturbines.com/technical.htm>. Accessed 29 Feb 2008.
- (2) Kobold turbine. http://www.dpa.unina.it/adag/eng/renewable_energy.html. Accessed 29 Feb 2008.
- (3) Salter, S.H. and Taylor, J.R.M. (2006). Vertical-axis tidal-current generators and the Pentland Firth. *Proc. I. Mech E.*, Vol.221, Part A: J Power and Energy, 181-199.
- (4) Loth, J.L. and McCoy, H. (1983). Optimization of Darrieus turbines with an upwind and downwind momentum model. *J. Energy* Vol.7, No.4, 313-318.
- (5) Blue Energy Canada Inc. <http://www.bluenergy.com>. Accessed 28 Feb 2008.
- (6) Furukawa, A. and Okuma, K. (2000). On applicability of Darrieus-type cross flow water turbine for abandoned hydro and tidal powers. *World Renewable Energy Congress VI (WREC2000)*, 2622-2625.
- (7) Tidal Energy Pty Ltd. <http://tidalenergy.net.au>. Accessed 29 Feb 2008.
- (8) New Energy http://irap-pari.nrc-cnrc.gc.ca/success/new_energy_e.html. Accessed 29 Feb 2008.
- (9) Ponta, F. and Dutt, G.S. (2000). An improved vertical-axis water-current turbine incorporating a channeling device. *Renewable Energy* Vol.20, 223-241.
- (10) Clean Current <http://www.cleancurrent.com/>. Accessed 28 Feb 2008.
- (11) Kirke, B.K. (2006). *Developments in ducted water current turbines*. <http://www.cyberiad.net>. Accessed 28 Feb 2008.
- (12) Kirke, B.K and Lazauskas, L. (1991). Enhancing the Performance of a Vertical Axis Wind Turbine Using a Simple Variable Pitch System. *Wind Engineering* Vol. 15, No.4.
- (13) Robinson, M.L. (1981). The Darrieus wind turbine for electrical power generation. *J. Royal Aeronautical Soc.*, June, 1-9.
- (14) Storer, R.G. (1981). *End of grant report "Vertical Axis Wind Turbine."* Dept of National

- Development and Energy, Canberra, Aust. Report NERDDP/EG/81/25.
- (15) Coastal Hydropower Corporation. <http://www.coastalhydropower.com>. Accessed 28 Feb 2008.
 - (16) Lazauskas, L. and Kirke, B.K. (1992). Performance Optimization of a Self-Acting Variable Pitch Vertical Axis Wind Turbine. *Wind Engineering* Vol.16, pp.10-26.
 - (17) Kirke, B.K. *Evaluation of self-starting vertical axis wind turbines for stand-alone applications*. PhD Thesis, Griffith University, 1998.
 - (18) Kirke, B.K. (1997). Cambered Blades: A New Way to Overcome VAWT Self-Starting Problems. *Aus-Pacific Wind Energy Workshop*, Monash University, Melbourne, Australia, July.
 - (19) Baker, J.R. (1983). Features to aid or enable self-starting of fixed pitch low solidity vertical axis wind turbines. *J. Wind Eng & Indust. Aerodynamics* Vol.15, 369-380.
 - (20) <http://www.cyberiad.net>. Accessed 28 Feb 2008.