Improving the cost-effectiveness of Darrieus hydrokinetic turbines

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Summary: Contrary to popular belief, Darrieus hydrokinetic turbines (HKTs) can be just as efficient as axial flow turbines. Their advantages include (i) straight untwisted blades which are relatively easy to construct, (ii) insensitivity to changes in flow direction, and (iii) rectangular swept area, facilitating close packing and ducting, which can increase power output from a given site. In their basic fixed pitch form they suffer from poor starting torque, low efficiency, shaking and torque ripple, but design improvements can eliminate or greatly reduce these disadvantages and greatly improve cost-effectiveness. This paper evaluates these options.

Introduction

It is widely believed that Darrieus hydrokinetic turbines (HKTs) are inherently less efficient than axial flow turbines, but this is not true. Two dimensional modelling by [1] of a Darrieus HKT with a simple passive variable pitch system predict a peak performance coefficient (efficiency) C_P of 0.47, a 50% increase over the same turbine with fixed pitch, along with an 8-fold increase in starting torque, shaking reduced by half and a large improvement in torque ripple. This prediction does not allow for radial arm drag losses, but [2] has measured a C_P of 0.5, as high as any reported for any form of HKT, with a combination of (i) active variable pitch and (ii) blades cantilevered from arms above water level, thereby eliminating arm drag losses. Several other measures have been shown to improve C_P, including improved blade profiles, reduced arm drag and blade tip losses, increased channel blockage, close-packed arrays of counter-rotating turbines, ducts and diffusers, and these are evaluated below.

High solidity and low tipspeed ratio result in low efficiency for fixed pitch Darrieus HKTs

Three factors lead to higher solidity σ in HKTs than in equivalent wind turbines: (i) Fluid dynamic forces are greater in water than in air, so HKT blades must generally be more robust, (ii) Wind turbine blade speeds are limited only by noise issues, but cavitation becomes an issue for HKT blades travelling at velocities relative to the water exceeding about 10 m/s (depending on blade profile, lift coefficient and depth of submergence). This limits λ to about 3 in a flow of 2.5 m/s. (iii) For Darrieus wind turbines, inertial ("centrifugal") forces typically exceed aerodynamic forces so the net force on blades acts outwards and slender troposkein blades which act in tension can be used without radial support arms, or at worst with slender low drag arms away from the equator. But in water, fluid dynamic forces generally exceed inertial forces and the net force on upstream blades is inward, so robust radial arms are unavoidable and parasitic drag losses from these arms increase steeply with λ, as shown by [3]. High σ in turn leads to peak C_P being reached at lower λ. It has been found in practice that optimum C_P is generally achieved at λ between 2 and 3 (see for example [4]). Fixed pitch blades stall at λ below about 3, greatly reducing efficiency and causing shock loading.

Improvements with variable pitch

Fixed pitch HKTs with both straight and helical blades were tested in open water by mounting in front of a vessel and driving the turbine through still water at a controlled speed. They were found to have very little starting torque and peak C_P no higher than 0.25 [5]. A 2-D double multiple streamtube (DMST) model (i.e. one without allowance for parasitic arm drag effects) was adapted to model the performance of fixed and variable pitch straight blade HKTs, and as mentioned above, indicated substantial improvements in starting torque, peak C_P, shaking and torque ripple [1]. Open water tests by the present author on a similar sized but not identical turbine with passive sinusoidal variable pitch showed C_P up to 0.31, a 24% improvement over fixed pitch, with much improved starting torque and reduced shaking. Measured C_P was lower than predicted, probably due to parasitic drag. Tests on a vertical axis wind turbine with a similar passive sinusoidal pitch mechanism also showed a marked improvement in starting torque.

Numerous sophisticated systems for active variable pitch, such as that used by [2] involving sensors, microprocessors and stepper motors to maintain optimum blade pitch and angle of attack α for all λ have been patented, but the present author believes that these are not necessary because tidal flow velocities change only slowly and the torque load on the turbine can be controlled so as to track the optimum λ, so that only one pitch regime is needed to give optimum α at optimum λ, and this can be achieved with a simple cam mechanism.

Reducing parasitic drag losses

Measurements by [4] show that parasitic loss due to blade tip losses and drag on the radial arms supporting the blades can be very serious, especially at higher λ, but can be minimised by (i) using arms with low drag and (ii) attaching arms to the ends of the blades rather than at points in from the ends which minimise blade bending moments. [2] has shown that C_P up to 0.5 can be achieved by a combination of active variable pitch and blades cantilevered from arms above water level, thereby eliminating arm drag losses. But this greatly increases blade bending moments and is probably feasible only in calm water.

Close packing, counter-rotating turbines, channel blockage, ducts and diffusers

[6] reports a 25% increase in the power output of 2 turbines if they are counter-rotating and placed close together. An array of close-packed counter-rotating turbines across the flow would be feasible at sites where the flow direction reverses. Such an array could achieve significant blockage and high C_P as reported by [7] in a narrow channel with high impedance, as discussed by [8], where this blockage would not significantly reduce flow and upset ecosystems.

[9] reports power augmentation factors up to about 4 on an axial flow wind turbine model with a duct and flanged diffuser, and it is likely that similar results could be achieved with a single cross flow HKT, but this power augmentation is achieved by drawing in flow from an area larger than the turbine swept area, which would not work with close-packed turbines. Also the diffuser structure is large and unidirectional, and would require fairly wide turbine spacing to enable it to yaw to follow reversing flows. A simple symmetrical duct tested by [4] increased turbine output by up to 74% and torque ripple was reduced at $\lambda \geq 2.75$, but increased at lower λ. However [10] found at $\lambda = 2$, use of a slightly different shaped duct reduced the torque ripple by a factor of 4.15 and the Cp increased by 57%. It appears therefore that there is room for further investigation of the effect of duct profile on torque ripple.

Conclusions

Straight blade Darrieus HKTs with simple passive pitch control, close packed, possibly with fairings which double as symmetrical ducts around support structures, offer a combination of low cost of construction with enhanced power output. In high impedance channels, high blockage can greatly increase power output.

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