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Tests on two small variable pitch cross flow hydrokinetic turbines

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ABSTRACT

Cross flow hydrokinetic turbines (HKTs) have some advantages and some disadvantages compared to axial flow HKTs. Fixed pitch cross flow HKTs suffer from lack of starting torque, torque ripple and shaking. It has been shown theoretically that these problems can be greatly reduced by means of variable pitch, but there is very little experimental data available on the actual performance of variable pitch HKTs. Two small cross flow hydrokinetic turbines with sinusoidally pitching straight blades were tested by driving them through still water to simulate a stationary deployment in a tidal flow. A 1 m diameter turbine with a passive eccentric mechanism was tested in open water, and a 0.5 m diameter turbine with cam-driven pitch was tested in a laboratory tow tank. A strong Reynolds number effect was observed, with peak performance coefficients ranging from 0.1 for the 0.5 m diameter turbine at 0.5 m/s in the towing tank, up to about 0.32 for the 1 m diameter turbine in open water at about 1 m/s, suggesting that larger turbines can be expected to perform better. CFD and streamtube predictions are compared with experimental data. Two-dimensional predictions, i.e. those ignoring parasitic drag loss, are shown to over-predict performance, and there is a need for modeling that accounts for these losses.

Introduction

Hydrokinetic turbines (HKTs) are analogous to wind turbines in that they convert kinetic energy in a moving fluid to mechanical shaft energy, but they do so in water rather than in air. Cross flow turbines in which the fluid flow is essentially normal to the axis of rotation are commonly referred to as "vertical axis" turbines because the axis of rotation is usually vertical as shown in Fig. 1, but it may be oriented horizontally—see for example the Ocean Renewable Power Company (ORPC) turbine (http://www.orpc.co).

Although the fluid dynamic principles governing the behavior of HKTs are in most respects the same as for wind turbines, there are some significant differences:

(i) Unlike wind turbines where the only limitations on blade speed are mechanical stress and noise level, HKT blade speed through the water is limited to about 10 m/s due to the danger of cavitation, although this limit depends to some extent on several factors such as blade cross section, lift coefficient and depth of submergence. This places a limit on tipspeed ratio λ, especially at sites with high flow velocities and corresponding high power density which are the most economically attractive. The factors influencing the onset of cavitation are discussed in (Batten et al., 2008). Cavitation problems can be reduced by (i) selecting a suitable blade profile which does not develop a high peak suction pressure, (ii) maintaining a low angle of attack, (iii) reducing the blade speed by reducing the tipspeed ratio, and (iv) increasing the depth of submergence.

(ii) Because the density of water is about 830 times higher than that of air and ambient flow velocities are typically several times lower than the wind velocities necessary for wind turbines to be viable, fluid dynamic forces on hydrokinetic turbine blades typically exceed inertial forces, unlike those on small wind turbines. This has implications for the structural design of blades and for the design of passive pitch control systems, since these systems on vertical axis wind turbines commonly use inertia to stabilize blade pitch (Kirke and Lazauskas, 2011), but this is not practicable for HKTs since inertial forces are very much lower.

Cross flow HKTs

The advantages and disadvantages of cross flow versus axial flow HKTs have been discussed by numerous authors—see for example (Kirke and Lazauskas, 2011), but for convenience are recapped here. Oriented with the shaft vertical, cross flow HKTs have at least four major advantages over axial flow HKTs:

(i) They are insensitive to flow direction unless they have a pitch control system which requires orientation to the flow
(ii) The gearbox (if used) and generator can be located above water level or just below the surface where they are easily accessible for maintenance
(iii) Several mass-produced, manageable sized turbines can be stacked in modular fashion on the same shaft to produce power equivalent to a single large turbine

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Notation

A	turbine swept area
c	blade chord length
C_p	performance coefficient or power coefficient = fraction of incident kinetic energy flux converted to shaft power $P/(½\ \rho\ A\ V_{inf}^3)$
n	number of blades
P	power
r	turbine radius
Re	blade chord Reynolds number = $V_{rel}\ c/\nu$
T	torque
TSR	tipspeed ratio = λ
V_b	blade speed = Ωr
V_{inf}	towing speed
V_{rel}	blade velocity relative to water
α	angle of attack
γ	pitch amplitude
λ	tipspeed ratio = V_b / V_{inf}
ν	kinematic viscosity
ρ	water density
σ	solidity = nc/r
Ω	angular velocity

(iv) Having a rectangular swept area, cross flow turbines with straight blades can be close-packed more effectively than axial flow turbines, resulting in increased turbine efficiency and tidal farm power (Willden and Nishino, 2014; Cooke et al., 2014).

Although various cross flow HKT designs have been proposed, some based on the Savonius or "S rotor" and some based on other drag type machines, these are inherently material-intensive and inefficient, and the straight blade Darrieus geometry shows the most promise for large scale power generation.

The biggest drawbacks of the fixed pitch Darrieus geometry are

(i) Blade stall, leading to low or negative torque at low λ, necessitating motor start or a hybrid Savonius–Darrieus configuration in tidal streams which stop and reverse four times per day. This arrangement has been used on Darrieus wind turbines like the one as shown in Fig. 2, which was tested at the Weapons Research Establishment (now DRCS), Salisbury, South Australia in the late 1970s (Robinson, 1981). The Savonius rotor provides starting torque and the Darrieus generates power at operating tipspeed ratios. This system has not to the author's knowledge been used on HKTs.

(ii) Fluctuating radial and tangential forces on blades, leading to torque ripple and shaking of the turbine, especially at low tipspeed ratios where blades stall twice per revolution. For example the speed of the wind turbine shown in Fig. 2 had to be limited due to severe shaking (Robinson, 1981). By pitching blades so as to reduce or limit stall, variable pitch can ensure adequate starting torque and can substantially reduce radial and tangential force fluctuations (Lazauskas and Kirke, 2012).

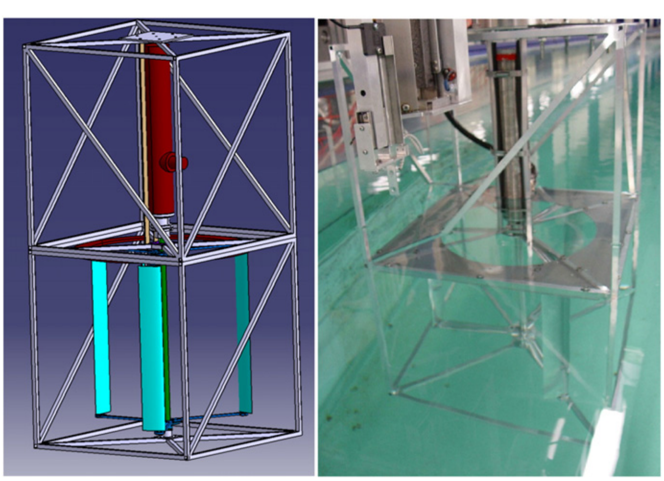

Fig. 1. Vertical axis HKT model test rig: CAD drawing left, and turbine in towing tank at right.

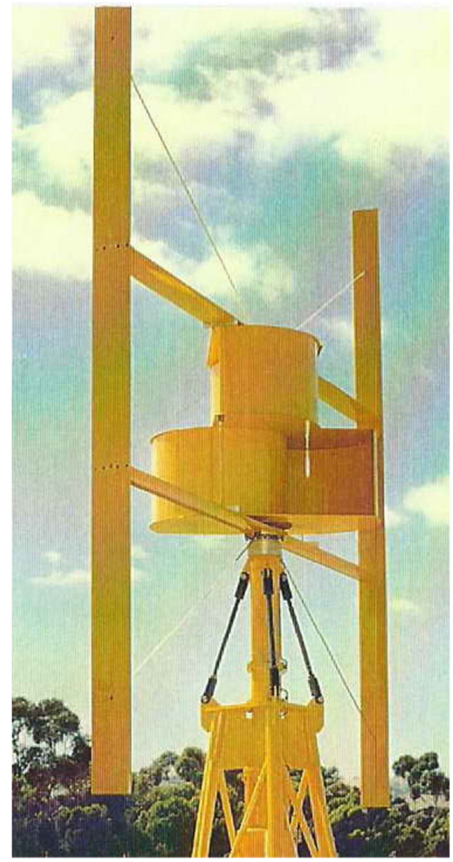

Fig. 2. A hybrid Savonius–Darrieus wind turbine.

Pitching blades to avert or minimize stall

Fig. 3 after Lazauskas (2008) shows how the angle of attack α of a fixed pitch Darrieus turbine varies with azimuth angle θ as tipspeed ratio λ increases, and the pitch amplitude γ necessary to limit α to 10° and hence avoid stall, assuming a stall angle of 10°. While this is only a typical figure for low Re operation and does not take into account Re effects (higher stall angle at higher Re—see Fig. 4) or dynamic stall effects which increase the stall angle when α is increasing and decrease it when α is decreasing, it gives a general indication of the fact that the required pitch amplitude decreases as λ increases.

It follows that it is desirable to vary the pitch amplitude if the turbine is to operate at varying λ, for example for a large wind turbine with a lot of inertia which is unable to vary its speed quickly to track sudden short term gusts and lulls and so maintain constant λ (although modern wind turbines do operate at varying speed to track more long-term changes in wind speed). But the velocity of river and tidal flows in which HKTs operate changes only slowly (unless the flow is highly turbulent, in which case it is probably impossible to track changes in velocity). Thus a maximum power point tracker should be able to vary the