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# Tests on ducted and bare helical and straight blade Darrieus hydrokinetic turbines

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ABSTRACT

Despite much optimistic language on commercial websites, little data is available on actual performance of hydrokinetic turbines. This paper summarises the findings of a series of tests on several Darrieus type cross flow hydrokinetic turbines (HKTs). Although this type of hydrokinetic turbine (HKT) has some advantages over axial flow turbines, fixed pitch Darrieus HKTs also have some drawbacks, including inability to self-start under load, low efficiency and shaking. Variable pitch has been suggested to increase starting torque and efficiency, ducts to increase power output and helical blades to produce smooth torque. To assess each of these modifications, tests were conducted in Australia and Canada on HKTs with fixed and variable pitch straight blades, fixed helical blades, with and without a slatted diffuser, by mounting each turbine in front of a barge and motoring through still water at speeds ranging from less than 1 m/s up to 5 m/s. The diffuser increased the power output by a factor of 3 in one configuration but considerably less in others. A reason for this finding is suggested. The maximum coefficient of performance Cp of the fixed pitch straight blade and helical turbines without a diffuser ranged from about 0.25 at 1.5 m/s down to less than 0.1 at 5 m/s, while Cp for those with a diffuser ranged from about 0.45 down to about 0.3. Fixed blade turbines, both straight and helical, exhibited low starting torque, while variable pitch turbines started easily. Considerable differences in Cp were observed for the same turbine configuration at different speeds. The turbine with fixed pitch, straight blades was found to shake violently due to cyclical hydrodynamic forces on blades, while the helical and variable pitch turbines did not shake excessively. These findings suggest that variable pitch cross flow HKTs should be further investigated.



## 1. Introduction

Whether blades are straight, helical or troposkein, Darrieus type hydrokinetic turbines (HKTs) have some advantages over axial flow turbines:

1. When oriented with axis vertical, they do not need to yaw with changes in flow direction
2. When oriented with axis horizontal they can still accept flow reversal, e.g. in tidal currents, without yawing.
3. In turbulent flows, or where the axis of rotation is not oriented exactly normal to the flow, they can generate some additional power from the axial component of flow, for 2 reasons: (i) straight blade turbines normally have radial arms (spokes) of hydrofoil section which may behave to some slight extent like Wells turbines, thereby contributing some power, while the ends of troposkein blades are inclined to the axis of rotation, and so also behave to some extent like Wells turbines. (ii) part of each blade on its downstream pass is exposed to undisturbed flow which has not already passed through the upstream blade path, so that the effective swept area is increased [1].
4. Blades are usually untwisted and of uniform cross section, making them easy to mass produce by aluminium extrusion or FRP (fibre reinforced plastic or fibreglass) pultrusion.
5. When the turbine is oriented with axis vertical, it can directly drive a generator above water level, making the generator more accessible.

However fixed pitch Darrieus HKTs also have some drawbacks, which have been discussed in detail in [2] and are summarized below.

1. Failure to self-start under load. The angle of attack $\alpha$ varies with azimuth angle $\theta$ and this variation is very large at low tipspeed ratios $\lambda$. This means blades are stalled for much of the time when starting, so they do not develop enough average starting torque over a revolution to reliably self-start, especially when

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driving a generator via a high step gear ratio or when blades are dirty.

2. Low efficiency. Unless turbines reach a tipspeed ratio of 3–4, blades will experience stall and efficiency will be low.
3. Vibration/shaking/torque ripple. Fixed pitch Darrieus HKTs tend to vibrate due to cyclically varying angle of attack and hence fluid dynamic forces on blades, with each blade experiencing two peaks in both radial and tangential force per revolution approximately 180° apart. The upstream peaks are typically much larger than the downstream peaks, so a 3 blade turbine will typically experience 3 major peaks per revolution. This problem is not related to mass balance of the rotor. The variation in tangential force, commonly referred to as "torque ripple," affects the transmission, while the variation in radial force affects the support structure, and if this frequency coincides with the natural frequency of the support structure it can be destructive.

## 2. Testing program

Theoretical investigations, flow table studies and initial small scale model testing [3] suggested that a short, wide angle slatted diffuser could potentially increase the power output of a wind turbine or HKT by a factor of up to about 3. The slats introduce high energy flow from outside the diffuser into the flow downstream from the turbine, preventing separation even in a wide angle diffuser [3,4]. While such an arrangement is not likely to prove economic for wind turbines, it looks more attractive for HKTs.

### 2.1. Tests in Australia

To investigate the power augmentation capability of such a diffuser (also called a duct or a venturi) on a Darrieus type HKT, tests were conducted on the Nerang River in Queensland, Australia on an HKT with 4 straight, passive variable pitch blades of 0.07 m chord length and cambered FX 63-137 section, with and without a diffuser. The turbine was 1.2 m high × 1.2 m in diameter, and the diffuser had 5 slats on each side, forming a flow passage with a slight contraction from the inlet, expanding to 2.4 m wide at the outlet (Fig. 1). The top and bottom of the diffuser were flat, and the spokes were covered by end plates in the planes of the top and bottom plates to minimize parasitic drag loss. This turbine was tested on a motorized barge, shown in Fig. 1, at speeds up to 0.91 m/s, the maximum speed achievable with the 30 kW (40 HP) outboard motor available at the time. Input water power, i.e. kinetic energy flux $P_w$, was calculated from the turbine swept area and the barge speed, which is equivalent to current speed V relative to a turbine mounted on a stationary platform, measured with a Swoffer propeller type current velocity meter (Fig. 2), held on a pole well to the side and in front of the turbine in undisturbed flow. $P_w$ is given by $P_w = ½\ \rho AV^3$, where $\rho$ = water density = 1000 kg/m$^3$, A = swept area = $1.2 \times 1.2 = 1.44$ m$^2$ and V = barge speed relative to water, equivalent to current speed for a fixed turbine in a flow.

Shaft torque was measured by two spring balances on a rope around a pulley, and rotational speed was measured by timing 10 revolutions. Shaft power $P_s$ is simply the product of torque (Nm) times angular velocity in radians/sec, and coefficient of performance Cp is the ratio of shaft power $P_s$ to the kinetic energy flux through the turbine $P_w$. Cp is a measure of efficiency, but in fact the theoretical maximum shaft power that can be extracted from a turbine in open flow, known as the Betz limit, is $0.593P_w$, so it is sometimes argued that the true efficiency should be defined as $P_s/(0.593P_w)$. The fact that a diffuser can augment the power output of a turbine by a factor of 3, it would appear that the Betz limit no longer applies, but in fact this augmentation is achieved by extracting power from a flow area greater than the swept area of the turbine itself, so the effective "swept area" is greater.

There were concerns that the low blade chord Reynolds numbers, ranging from a maximum of about 170,000 down to less than 70,000 for blades moving downstream would result in low efficiency, so a scaled up version 2.4 m high and 2.4 m diameter was

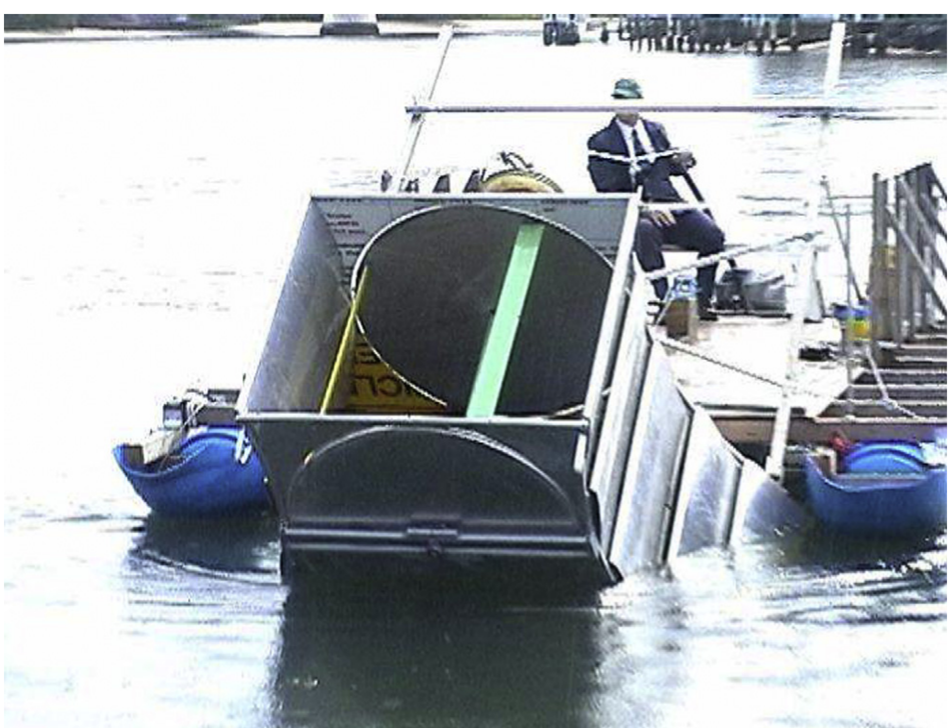

**Fig. 1.** 1.2 × 1.2 m turbine in duct, raised to show turbine.