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An experimental investigation into the influence of unsteady wind on the performance of a vertical axis wind turbine

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HIGHLIGHTS

- ▶ Experiments on a wind tunnel scale VAWT were conducted in unsteady wind conditions.
- ▶ Varying tip speed ratios and amplitudes were tested and the results presented.
- ▶ The unsteady power coefficient of the VAWT does not trace the steady CP curves.
- ▶ Small amplitudes have no effect on cycle CP while large amplitudes are detrimental.
- ▶ Mean λ below peak performance show hysteresis in CP curve while high λ do not.

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ABSTRACT

An experimental investigation was carried out on a wind tunnel scale vertical axis wind turbine with unsteady wind conditions. The wind speed at which testing was conducted was 7 m/s (giving a Reynolds number of around 50,000) with both 7% and 12% fluctuations in wind velocity at a frequency of 0.5 Hz. Rotational speed fluctuations in the VAWT were induced by the unsteady wind and these were used to derive instantaneous turbine rotor power. The results show the unsteady power coefficient (CP) fluctuates following the changes in wind speed. The time average of the unsteady CP with a 7% fluctuation in wind velocity was very close to that with steady wind conditions while 12% fluctuations in wind speed resulted in a drop in the mean CP, meaning unsteady winds of such amplitudes are detrimental to the energy yields from these wind turbines. At mean rotational speeds corresponding to tip speed ratios (λ) beyond peak CP, no significant hysteresis was observed for both 7% and 12% fluctuations. However, substantial hysteresis is seen for conditions where mean λ is below peak CP.

1. Introduction

The use of wind turbines has risen rapidly in recent years because of the potential that they offer for carbon free power generation. Winds are usually unsteady with high levels of turbulence for significant proportions of the time, resulting in air flows characterised by rapid changes in speed and direction. It has been pointed out several times in the literature [1–4] that vertical axis wind turbines (VAWTs) may be more appropriate for urban applications because of a number of distinct advantages it presents over the conventional horizontal axis wind turbines (HAWTs). These advantages include no need to include a yawing mechanism to adjust the rotor to the changing wind direction, ease of maintenance due to the location of the gearbox – generator system at the base of the turbine, as well as potentially better performance in unsteady and skewed wind conditions [5–7].

However, very little work has been carried out into the effects of VAWT performance in unsteady wind conditions. The vast majority of research published (both numerical and experimental) has been with steady wind flows probably because the detailed analyses of blade loading and rotor performance are well established and fairly straightforward. However, there have been a handful of efforts (mostly numerical) that have attempted to provide initial understanding of the VAWT performance in unsteady wind. Earlier attempts to understand the performance of VAWTs in unsteady wind were carried out by Mcintosh et al. [8,9] through numerical modelling. The VAWT was subjected to fluctuating free stream of sinusoidal nature while running at a constant rotational speed.

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Nomenclature

A	rotor frontal swept area, 2RL
c	blade chord
CP	power coefficient
f_c	characteristic frequency of unsteady wind
I_{rig}	rotor rotational mass moment of inertia
L	blade length
N	number of blades
P_B	blade power (three blades)
P_w	wind power
R	rotor radius
T_{app}	applied brake torque
T_B	blade torque (three blades)
T_{res}	resistive torque
V_{wind}	instantaneous wind speed
V_∞	free stream wind speed
V_{amp}	amplitude of fluctuation of unsteady wind
V_{mean}	mean speed of unsteady wind
λ	tip speed ratio, $R\Omega/V_\infty$
λ_{mean}	tip speed ratio corresponding to Ω_{mean}
ξ	rotor angular acceleration
ρ	air density
σ	rotor solidity, Nc/R
Ω	rotor angular speed
Ω_{mean}	in unsteady wind, mean of Ω
HAWT	horizontal axis wind turbine
VAWT	vertical axis wind turbine

An increase in energy extraction was attained using a rotational speed greater than the calculated steady state maximum. The over-speed control technique resulted to a 245% increase in energy extracted. Further improvements in the performance can be attained by using a tip speed ratio feedback controller incorporating time dependent effects of gust frequency and turbine inertia giving a further 42% increase in energy extraction. At low frequencies of fluctuation (0.05 Hz) away from stall, the unsteady CP closely tracks the steady CP curve. However at higher frequencies (0.5 Hz), the unsteady CP is seen to form hysteresis loops with averages greater than steady predictions.

Hayashi et al. [10] examined the effects of gusts on a VAWT by subjecting a wind tunnel scale rotor to a step change in wind velocity. Two types of control were implemented: constant rpm and constant load torque. When subjected to a step change in wind speed from 10 m/s to 11 m/s under constant rpm control, the VAWT torque was observed to respond almost instantaneously and attained a steady state in less than 3 s. However when constant load torque control was employed, the initial response is similar to the constant rpm control where the torque instantly jumps to a higher level. The subsequent behaviour is a combination of a gradual increase in rpm with a slow decrease in torque until steady state is attained. Despite an observed transient VAWT response that does not follow steady state power curves, they contend that the adopted step change in wind speed is not normally observed in the real world and most likely a more gradual increase is expected. The VAWT behaviour will thus follow a quasi-static condition during the gust.

In 2010, Kooiman and Tullis [11] experimentally tested a VAWT within the urban environment to assess the effects of unsteady wind on aerodynamic performance. Temporal variation in speed and direction was quantified and compared to a base case wind tunnel performance. Independence of the performance in directional fluctuations was seen while amplitude-based wind speed fluctuation decreased the performance linearly. For their particular urban site, the degradation in performance was deemed minimal.

Danao and Howell [12] conducted CFD simulations on a wind tunnel scale VAWT in unsteady wind inflow and have shown that the VAWT performance generally decreased in any of the tested wind fluctuations. The amplitude of fluctuation studied was 50% of the mean wind speed and three sinusoidal frequencies were tested: 1.16 Hz, 2.91 Hz, and 11.6 Hz where the fastest rate is equal to the VAWT rotational frequency. The two slower frequencies of fluctuation showed a 75% decrease in the wind cycle mean performance while the fastest rate caused a 50% reduction. Closer investigation revealed that for a 2.91 Hz fluctuation rate a large hysteresis is seen in the unsteady CP of the VAWT within one wind cycle. This hysteresis occurs in the positive amplitude portion of the wind fluctuation where the blades passing the upwind progressively stall at earlier azimuths and experience very deep stall due to significant reduction in the effective λ. Negative amplitude in wind fluctuation does not produce significant hysteresis. However, the unsteady CP traces a curve that does not follow the steady CP curve but somehow crosses it down to a lower level performance curve.

Following the work of Hayashi in 2009, Hara et al. [13] studied the effects of pulsating winds on a VAWT and the dependence of the performance to changes in the rotor's moment of inertia. The fluctuating wind was not sinusoidal but alternating gusts and lulls that were equally distant from a mean wind speed. This was implemented by a blade pitch-controlled fan blowing to an Eiffel-type wind tunnel with the rotor 1.5 m from the tunnel outlet. Results show a phase delay in the response of the rotational speed from the wind variation but held a constant value of about $\pi/2$ regardless of amplitude. This was explained as an effect of the distance of the VAWT from the tunnel outlet where the hotwire was installed. The energy efficiency of the VAWT was observed to be constant in changing rotor moment of inertia and fluctuation frequency but a decrease is seen when fluctuations have large amplitudes. Further work for a larger scale VAWT using numerical techniques confirm their experimental observations and a locus of torque is produced as the VAWT response to the cyclic changes in wind speed.

In 2012, Scheurich and Brown [14] published their findings on a numerical model of VAWT aerodynamics in unsteady wind conditions. The fluctuating wind had a mean speed of 5.4 m/s with a fluctuating frequency of 1 Hz. Different fluctuation amplitudes were investigated for three blade configurations: straight, curved, and helical. Constant rotational speed was used in the numerical simulations and the boundary extents were far enough for the model to be considered as open field. Both straight and curved blades exhibited considerable variation in blade loading which is also observed in steady wind results. These variations in CP over one revolution are more significant than those induced by the unsteadiness of the wind. Helical blades perform much better with the unsteady CP tracing the steady performance curve quite well. Overall performance degradation is observed when fluctuation amplitudes are high while the effect of frequency is minor for practical urban wind conditions. Hysteresis loops of the CP are seen on the helical configuration that extend beyond the steady CP variation especially for the high frequency of wind fluctuation.

The conflicting conclusions from previous published research suggest that very little is still understood about the performance and aerodynamics of VAWTs in unsteady winds. Any generalisations made about VAWT performance in the urban environment may well be completely erroneous.