Improving safety and performance of small-scale vertical axis wind turbines

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Abstract

Although horizontal axis wind turbines (HAWT) are considered more efficient in operation than their vertical axis wind turbine (VAWT) counterpart and are more commonly used in wind farms as large wind turbines, the VAWT may offer greater advantages in safety and operation when it comes to their application within the urban environment. Yaw control systems are an essential requirement for the safe operation of HAWT, which are costly and require high levels of maintenance, but are inherently unnecessary for VAWT. At low blade speed ratios, the performance of VAWT degrades owing to strong dynamic stall effects. This necessitates VAWT operation at high blade speed ratios to suppress them. However, the consequent large rotational speeds lead to hazardous operation especially in confined urban areas. Thus to improve the low blade speed performance, a preliminary experimental investigation has been carried out at the Aerodynamics Laboratory of the University of New South Wales on an H-type VAWT blade that employed zero-net mass flux actuation. This technique has traditionally been used for static stall delay and flow separation mitigation on aircraft wings. In the present study, large relative angles of incidence were simulated by sinusoidally oscillating the blade about its quarter-chord, and resulted in the formation of dynamic stall vortices. The application of zero-net mass flux actuation was found to have a beneficial effect on the blade aerodynamic performance by either suppressing dynamic stall or delaying its onset to higher angles of attack. This study, therefore, suggests that reduced oscillatory loads and more robust output power can be achieved with zero-net mass flux actuation on VAWT operating at low blade-speed ratios. Consequently, the findings have positive practical implications for the design of small-scale VAWT for widespread use in the urban environment.

Keywords: renewable energy; vertical axis wind turbine; dynamic stall; zero-net mass flux actuation

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
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<tbody>
<tr>
<td>b</td>
<td>blade span length</td>
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<td>c</td>
<td>chord length</td>
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<tr>
<td>C_l</td>
<td>lift coefficient</td>
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<tr>
<td>C_p</td>
<td>pressure coefficient</td>
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<tr>
<td>C_m</td>
<td>momentum coefficient</td>
</tr>
<tr>
<td>f_j</td>
<td>actuation frequency</td>
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<tr>
<td>f_j*</td>
<td>non-dimensional frequency</td>
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<tr>
<td>L</td>
<td>lift</td>
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Greek Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
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<tbody>
<tr>
<td>α</td>
<td>angle of attack</td>
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<tr>
<td>α_m</td>
<td>mean angle of attack</td>
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<tr>
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<td>minimum angle of attack</td>
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<tr>
<td>α_max</td>
<td>maximum angle of attack</td>
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<tr>
<td>Δα</td>
<td>oscillation amplitude</td>
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1. Introduction

Deployment of small-scale wind turbines on rooftops in urban environments has increased over the last decade due to rising energy costs, and the global need to reduce carbon and greenhouse gas emissions. Vertical axis wind turbines (VAWT) are well suited to such environments due to their inherent axisymmetric design obviating expensive yaw control systems required for horizontal axis wind turbines (HAWT) and allowing the gearbox and generator to be located on the ground. This arrangement offers two additional advantages over HAWT namely 1) easy access to facilitate turbine maintenance, and 2) reduced loads on the turbine tower to reduce material costs. These benefits are necessary for the installation and continued operation of cheap small-scale wind turbines.

Safe operation of VAWT in restricted urban spaces requires low rotational speeds to reduce noise, mechanical vibrations and proximity hazards. However, VAWT typically operate at high blade speed ratios between $\lambda = 4$ and 7 to mitigate complex blade-vortex interactions that manifest at low ratios from $\lambda = 1$ to 3. Rotational motion of VAWT blades about the turbine central shaft induces a relative flow velocity to the blades, $V_{rel}$, that is composed of the wind velocity, $V_w$, and the rotational velocity of the blades, $\omega R$, such that the blade geometric angle of attack, $\alpha$, is given by

$$\alpha = \arctan\left(\frac{\sin \psi}{\lambda + \cos \psi}\right)$$

where $\psi$ is the azimuth angle equivalent to $0^\circ$ when the blade leading-edge is parallel and facing into the wind. As such, large blade angles of attack up to $\pm 50^\circ$ can be experienced at low blade speed ratios. This results in strong dynamic stall effects and periodic shedding, advection and impingement of vortices on downstream blades which can cause undesirable blade vibrations and damage.

Dynamic stall influence on VAWT aerodynamics at low blade speed ratios has been thoroughly investigated. Analytical models, such as the double-multiple streamtube [1] and vortex [2, 3] methods, were employed in the past to estimate VAWT blade loads and power performance. These models were adequate for low solidity, high blade speed ratios but failed for low to moderate ratios, ostensibly due to dynamic stall effects, and corrections [4, 5] to the models had to be made. Dynamic stall occurrence on VAWT has since been observed experimentally by Fujisawa and Shibuya [6]. They captured the formation and shedding of two pairs of stall vortices using dye injection and particle image velocimetry (PIV) techniques in a water tunnel at a Reynolds Number of $R_e = 3 \times 10^3$ for blade speed ratios between $\lambda = 1$ to 3. PIV measurements at higher Reynolds Numbers of $R_e = 5 \times 10^4$ and $7 \times 10^4$ at $\lambda = 2$ have been obtained by Ferreira et al. [7, 8] to quantify the dynamic stall vortex evolution. Effects of blade pitch and canted blades on turbine performance has also been investigated by Fiedler and Tullis [9] and Armstrong and Tullis [10] respectively.

Significant improvements in computing power over the last decade have allowed computational fluid dynamics simulations to resolve complex VAWT flow fields and the dynamic stall vortex evolution. The results have demonstrated that, in general, three-dimensional simulations were required to accurately match experimental power coefficients [11-13]. Two-dimensional simulations predicted higher values as blade tip losses and support shaft effects significantly degraded turbine performance. Simulations of a small-scale H-type VAWT by McLaren et al. [13] found the maximum thrust force and onset of dynamic stall to progressively decrease and occur earlier, respectively, as the blade speed ratio decreased below the optimal value, $\lambda_{opt}$. Additionally, multiple vortices were shed and their effect on turbine performance was evident as oscillations in the instantaneous thrust curve.

Improving wind turbine blade aerodynamic performance has been investigated using passive vortex generators [14], as well as active flow control techniques such as blowing [15, 16]. Zero-net mass flux (ZNMF) actuation [17-19] is an alternative flow control technique that has been traditionally employed to delay static stall and mitigate flow separation on aircraft wings. As its name suggests, there is no net transfer of mass, but enhances surrounding flow through a non-zero transfer of momentum. This can be achieved using an oscillating piston or diaphragm operating within an enclosed cavity...
through an orifice. Additionally, this arrangement avoids the need for fluid reservoirs and complex plumbing necessary for steady blowing or suction.

ZNMF actuation on thick wind turbine blades including the IAI Pr8-SE [20] and NACA 4415 [21] airfoils has been investigated in the past. Although these studies found ZNMF actuation to have a beneficial effect by delaying airfoil stall, decreasing drag and reducing structural blade vibrations, they were limited to static tests and did not take into account any dynamic effects which are significant on VAWT, particularly at low blade speed ratios.

Therefore, the objective of this paper was to determine if ZNMF actuation has the potential to improve low blade speed VAWT performance when the dynamic motion of wind turbine blades is included, and therefore, increase its safety when operated in urban areas. Section 2 describes the experimental setup of the turbine blade, oscillation mechanism and ZNMF actuation. The results and discussion, including the implications of utilising ZNMF actuation to improve VAWT performance, are presented in Section 3, and conclusions are drawn in Section 4.

2. Experimental Setup

2.1. Blade Design & Test Facility

Experiments were conducted in the 0.76 m diameter open section wind tunnel located in the Aerodynamics Laboratory of the University of New South Wales which has a maximum turbulence intensity of 0.2% [22]. A thick NACA 0020 profile was used for the wind turbine blade with chord length of 207.5 mm and span of 300 mm, and was adequate to enclose a plenum chamber to generate ZNMF actuation. Endplates were attached to reduce three-dimensional spanwise effects. The freestream velocity was fixed at $V_w = 10 \text{ms}^{-1}$ corresponding to a Reynolds Number of $Re = 1.25 \times 10^5$.

A total of 25 pressure tappings were installed in the middle of the wing at the leading-edge and on the upper and lower surfaces. Pressure tappings located above the plenum chamber were installed by fitting 0.9 mm inner diameter brass tubing into pre-drilled holes from the upper surface, through the plenum chamber and into the blade. Care was taken to remove any irregularities at the surface.

2.2. Zero-Net Mass Flux Mechanism

ZNMF actuation was generated by the piston-type method described earlier using a modified air compressor connected to the plenum chamber inside the blade, through a $w = 1\text{mm}$ wide spanwise slot oriented perpendicular to the blade chord at $x/c = 0.028$, and calibrated with a hot-wire. A momentum coefficient, based on the maximum velocity during the blowing phase, of $C_{\mu} = 1.1 \times 10^3$ was used for all experiments. Actuation was fixed at $f_j = 47.5 \text{Hz}$ corresponding to a non-dimensional forcing frequency of $f_j^+ = 1$.

2.3. Oscillation Mechanism

Although the geometric angle of attack for a H-type VAWT blade is given by Eqn. (1), this preliminary investigation employed simpler sinusoidal motion to account for unsteady dynamic turbine effects. Sinusoidal blade motion about the quarter-chord was achieved using a motor and metal disk-conrod system. The conrod location on the metal disk determined the oscillation amplitude which was set at $\Delta \alpha = 40^\circ$ for the dynamic experiments, and the effect of ZNMF actuation on low blade speed ratios of $\lambda = 2.92, 2.37, 2$ and 1.57, which typically experience angles of attack of $\pm 20^\circ, \pm 25^\circ, \pm 30^\circ$ and $\pm 40^\circ$ respectively as shown in Fig. 1, was investigated by setting the mean angle of attack to $\alpha_m = 0^\circ, 5^\circ, 10^\circ$ and $20^\circ$ using an adjustable stand for the motor.
2.4. Data Acquisition & Processing

Instantaneous pressure data around the blade were recorded using the Turbulent Flow DPM-1041 Dynamic Pressure Measurement System containing 32 channels; each with its own pressure transducer accurate to within 0.3%. The frequency response of the 1.5 mm inner diameter 1800 mm long pressure tubing was found to be within 3 dB up to 135 Hz [23] and amplitude and phase distortions introduced by the tubing were corrected using the theory of Bergh and Tijdeman [24], and applying Fourier and Inverse Fourier Transforms to linearise the temporally-varying pressures. Data was sampled at 2 kHz to prevent aliasing of high frequencies and aerodynamic coefficients were obtained after phase-averaging the data over 50 cycles.

3. Results and Discussion

The four blade speed ratios investigated were found to fall into two groups based on the development of the pressure distributions, and the lift hysteresis loops. The higher blade speed ratios of \( \lambda = 2.92 \) and 2.37 were categorised into one group, while the other group consisted of the lower blade speed ratios \( \lambda = 2 \) and 1.57.

3.1. Blade Speed Ratios \( \lambda = 2.92 \) and 2.37

The pressure distribution developments during the unsteady blade motion on the suction surface for the higher demarcating blade speed ratio of \( \lambda = 2.37 \) with and without ZNMF actuation are shown in Fig. 2, while the lift hysteresis loops for both blade speed ratios of \( \lambda = 2.92 \) and 2.37 are presented in Fig. 3. The pressure distribution for \( \lambda = 2.37 \) steadily increased in suction at the leading-edge region up to a peak value of \( C_p = -4.23 \) at \( \alpha = 24.8^\circ \), before gradually decreasing as the angle of attack decreased. A close examination of the pressure distribution revealed a small suction wave to travel from leading-edge to trailing-edge at approximately \( \alpha \approx 24.3^\circ \) suggesting the shedding of a small leading-edge vortex. Subsequently, suction decreased over the body of the blade between \( x/c = 0.33 \) to \( x/c = 1 \) following the suction wave passage which indicated partial flow separation that initiated from the trailing-edge. A similar pressure distribution was obtained for \( \lambda = 2.92 \), however, no suction wave was observed in the results.

Application of ZNMF actuation was found to have a small effect on the pressure distribution. The peak suction increased by 4% to \( C_p = -4.40 \) and the suction wave magnitude slightly decreased. Additionally, a more gradual reduction in suction over the body of the blade took place.

The small effect of applying ZNMF actuation to the blade was also evident from the lift hysteresis loops, remaining essentially unaltered, in Fig. 3. For both blade speed ratios of \( \lambda = 2.92 \) and 2.37, lift increased linearly as the angle of attack increased with a slope of approximately 55% and 50% respectively of the theoretical slope as given by thin airfoil theory. For \( \lambda = 2.92 \), undulations in lift began at \( \alpha = 5^\circ \) with an approximate mean lift coefficient of \( C_l \approx 1.1 \) until stall at \( \alpha_{\text{max}} = 20^\circ \). These undulations were attributed to the shedding of small trailing-edge vortices observed in the pressure distribution. For \( \lambda = 2.37 \), no such oscillations in lift were found, and lift began to plateau at \( \alpha = 11.5^\circ \) with a lift coefficient of \( C_l \approx 1 \). The lift plateau began to decrease at \( \alpha = 17.5^\circ \) before undergoing a small surge at \( \alpha = 23.5^\circ \) due to
the formation and advection of the small leading-edge vortex. The ineffectiveness of ZNMF actuation to either improve or greatly alter the pressure distributions or lift hysteresis loops was ostensibly due to the flow already being attached, or at least partially attached, throughout the unsteady blade motion.

Fig. 2: Pressure Distribution Evolution for $\lambda = 2.37$; a) without actuation b) with actuation

![Fig. 2](image)

Fig. 3: Lift Coefficient Hysteresis Loops for a) $\lambda = 2.92$ and b) $\lambda = 2.37$

3.2. Blade Speed Ratios $\lambda = 2$ and 1.57

The temporal development of the pressure distributions on the blade suction surface for the other demarcating blade speed ratio of $\lambda = 2$ is shown in Fig. 4, and the lift hysteresis loops for both $\lambda = 2$ and 1.57 are presented in Fig. 5. Suction progressively increased in the leading-edge region as the angle of attack increased, similar to the pressure distributions in Fig. 2, to a peak value of $C_p = -4.90$ at $\alpha = 28.4^\circ$. However, this leading-edge suction suddenly collapsed a short time after at $\alpha = 29.6^\circ$, and the flow completely separated from the blade suction surface. The strong and broad suction wave that subsequently followed the abrupt loss of suction indicated the formation and convection of a strong leading-edge vortex along the blade chord. Flow appeared to remain separated from the blade surface until the minimum angle of attack $\alpha_{min} = -10^\circ$ was reached.

ZNMF actuation appreciably altered the pressure distributions for these lower blade speed ratios. For $\lambda = 2$, the peak suction was, again, increased by 9% to $C_p = -5.35$ but was now delayed to $\alpha = 29.6^\circ$. A more gradual collapse in the leading-edge suction subsequently occurred, and its severity was reduced as the leading-edge retained some suction to keep the flow partially attached to the blade. The broad suction wave was significantly suppressed as it was barely visible in the pressure distribution.

The evolution of the pressure distributions for $\lambda = 1.57$ was similar to $\lambda = 2$, with the peak suction value increasing by 15% from $C_p = -5.11$ to $-5.88$, and delayed from $\alpha = 32.2^\circ$ to $34.3^\circ$, with application of ZNMF actuation. However,
actuation did not suppress the leading-edge vortex nor maintain suction in the leading-edge region following its collapse, possibly due to a lack in the ZNMF momentum coefficient to overcome strong viscous effects. The convection speed of the leading-edge vortices was also estimated from the pressure distributions and was found to increase from $1.6U_\infty$ to $2.0U_\infty$ with actuation.

The alteration of the pressure distributions with ZNMF actuation was observed in the lift hysteresis loops, Fig. 5. The lift increased linearly with angle of attack with a slope of 57% and 60% of the theoretical $2\pi$ slope up to $\alpha = 10^\circ$ and $13.5^\circ$ at which the lift began to plateau for the blade speed ratios of $\lambda = 2$ and $1.57$ respectively. Actuation had little effect on the lift curve up to these points as the flow was already attached to the blade. For $\lambda = 2$, the mean lift coefficient during the plateau period was approximately $C_l \approx 1.0$, but decreased to $C_l \approx 0.95$ when ZNMF actuation was applied. In both cases, a surge in lift initiated at $\alpha = 28.9^\circ$, but was significantly reduced with actuation as the leading-edge vortex was suppressed.

For $\lambda = 1.57$, the mean lift coefficient, following the initial linear lift increase, was $C_l \approx 0.93$. Lift began to surge at $\alpha = 32.5^\circ$ before stalling at $\alpha = 38.3^\circ$. A similar mean lift coefficient was obtained with ZNMF actuation, but onset of lift surge was delayed until $\alpha = 35^\circ$ and stalled earlier at $\alpha = 37.6^\circ$. However, unlike $\lambda = 2$, the maximum lift coefficient was approximately the same regardless of ZNMF actuation, confirming its inability to suppress formation of the leading-edge vortex.

![Fig. 4: Pressure Distribution Evolution for $\lambda = 2$; a) without actuation b) with actuation](image1)

![Fig. 5: Lift Coefficient Hysteresis Loops for a) $\lambda = 2$ and b) $\lambda = 1.57$](image2)
3.3. Implications for Small-Scale VAWT

Development of the pressure distributions and the lift hysteresis loops suggested that ZNMF actuation is an effective flow control technique for VAWT blades when a leading-edge vortex forms, or flow has separated from the blade. Efficacy of the actuation then depends on its momentum coefficient to alter the separated viscous state of the flow.

Despite the ineffectiveness of ZNMF actuation to alter the flow for blade speed ratios above \( \lambda = 2.37 \), the results suggest how actuation could improve the performance of small-scale VAWT. Firstly, actuation did not appear to impede blade performances for blade speed ratios greater than \( \lambda = 2.37 \). Therefore, ZNMF actuation could be simply employed regardless of blade speed ratio to avoid complex and possibly expensive sensor and control systems; or only be activated at very low blade speed ratios below \( \lambda = 2 \) to save energy and prevent unnecessary power expenditure.

Secondly, ZNMF actuation can suppress formation and convection of small vortices thereby eliminating periodic power spikes or undulations typically observed at low blade speed ratios [13]. This will improve reliability and robustness of VAWT output power.

Thirdly, when suppression of vortices cannot be achieved, ZNMF actuation can delay the onset of the lift surge and shedding of the vortex, as well as alter the vortex convection speed. Careful timing of vortex shedding could prevent vortex impingement on downstream blades, which is experienced by the high solidity low blade speed ratio H-VAWT by McLaren et al. [13], improving downstream blade pass performance and reducing abrupt structural loads on the blade.

ZNMF actuation ultimately expands the operating envelope of small-scale VAWT to include lower blade speed ratios that suffer from degraded dynamic stall effects, increasing their safety and promoting their deployment in small and confined urban areas.

4. Conclusion

VAWT possess several advantages over HAWT to empower the common person in using renewable wind energy in built up environments. However, their deployment in small and confined urban areas may not be safe when operated at more efficient, high rotational speeds. An experimental investigation was, therefore, carried out to determine the efficacy of using ZNMF actuation to improve the performance, and hence safety, of VAWT at low blade speed ratios between \( \lambda = 2.92 \) to \( 1.57 \). Actuation was found to be effective in altering the development of the pressure distributions and lift hysteresis loops for very low blade speed ratios below \( \lambda = 2 \), which was predominantly characterised by the formation and convection of a strong leading-edge vortex. Based on the results, ZNMF actuation could:

1. be implemented in VAWT blades in two ways, to reduce either VAWT manufacturing costs or actuation power consumption;
2. improve reliability and robustness of VAWT output power during low blade speed ratio operation by completely suppressing small vortices; and
3. improve the downstream blade pass performance and reduce abrupt structural loads on the blade by delaying and carefully timing vortex shedding.

Although further work must be carried out to investigate the dependence of vortex suppression with ZNMF momentum coefficient on a VAWT model, the findings from this study are encouraging and have practical implications in the design and future deployment of small-scale VAWT in urban environments.

References


