Scaling of Vertical Axis Wind Turbine Dynamic Stall

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Nomenclature

- \( c \): Chord length of turbine blades
- \( K_c \): Dimensionless pitch rate
- \( R \): Radius of vertical axis turbine
- \( Re \): Reynolds number
- \( U_{\infty} \): Freestream velocity
- \( \alpha \): Angle of attack
- \( \Gamma \): Circulation
- \( \theta \): Azimuthal blade angle
- \( \lambda \): Tip speed ratio
- \( \nu \): Kinematic viscosity
- \( \Omega \): Rotation speed of vertical axis turbine

Abstract

Vertical axis wind turbines (VAWT) are an alternative to horizontal axis wind turbines (HAWT) for wind and tidal energy harvesting applications. Studies of vertical axis wind turbines have heavily invested in understanding the behaviour of the complete turbine, but often with only cursory assessment of the contributions of unsteady aerodynamics of individual blades. This paper experimentally explores the process of unsteady flow separation, or dynamic stall, of the flow around the blades of a gyromill-style vertical axis wind turbine, and the factors upon which its appearance and evolution rely.

Introduction

Wind and tidal energy harvesting have long been mainstays of a growing renewable energy generation industry. Horizontal axis wind turbines (HAWT) have been the dominant turbine form for decades, but there has at times been an interest in alternative configurations. Amongst these, the vertical axis wind turbine (VAWT) presents a number of potential advantages, but also significant technical challenges. Chief amongst the aerodynamic challenges posed by vertical axis wind turbines is the dynamic stall phenomenon. This unsteady flow separation is thought to induce undesirable structural vibrations, contribute to the production of noise, and have a deleterious effect on the efficiency of the turbine, and is a crucial problem to understand and address for more widespread adoption of vertical axis wind turbine technology.

The history of dynamic stall research is rich, but the highly nonlinear nature of the phenomenon, and the large parameter space within which the experimentalist must work, mean that previous results must be considered with caution when approaching the question of dynamic stall in a new application or context. Much previous work has been published on dynamic stall of helicopter blades, and of flapping wings or oscillating fins [1, 2, 3], but the combination of rotation and rapid blade incidence angle changes particular to vertical axis wind turbines warrants greater attention. Insufficient study of the relative importance of the kinematic parameters involved has been performed. Buchner and Soria [4] addresses the dynamic stall’s dependence on Reynolds number, while Ferreira et al [5] studies the effect of tip speed ratio, and also touches on the dependence of the flow on Reynolds number, but the dimensionless pitching rate, and its relevance to the onset and evolution of the dynamic stall are not addressed.

Dynamic Stall and its Governing Parameters

The bulk of the literature regarding the aerodynamics of vertical axis wind turbine blades considers the effect of tip speed ratio \( \lambda \),

\[
\lambda = \frac{R \Omega}{U_{\infty}}
\]

but without regard for the pitch rate of the blade itself. These are two distinct properties of the turbine and it is possible to vary the dimensionless pitch rate \( K_c \), defined by

\[
K_c = \frac{c \Omega}{2 U_{\infty}} = \frac{c}{2R}
\]

independently of the tip speed ratio. The definition of pitch rate, as used by Ferreira et al [5], reduces to a purely geometric form (equation 2), independent of the tip speed ratio if the tangential blade velocity is used as the reference velocity. It must be recognized therefore that the tip speed ratio is primarily a modulator of effective velocity relative to the turbine blade, whilst the dimensionless pitch rate is independent and separate. This has not been made clear in the available literature.

Of interest is the relatively low dimensionless pitch rate of the blades in the operational range for a vertical axis wind turbine, typically on the order of \( 0.1 \leq K_c \leq 0.2 \). Airfoils pitching at such low dimensionless rates typically undergo stall (if the angle of attack excursion is great enough), but it is debatable whether such pitch rates are sufficiently high for the stall to be considered “dynamic” stall. At these pitch rates, the flow separation from the upper surface of the airfoil is likely to begin near the trailing edge, with the point of separation moving rapidly forward as the stall progresses. Dynamic stall on the other hand is characterised by a strong separation of the boundary layer near the leading edge and subsequent roll-up into a leading edge vortex [1].

This reasoning holds for an airfoil undergoing a pure pitching motion. The situation which presents itself currently however, has an important complicating factor. The existence of a velocity modulation relative to each turbine blade, as a result of...
The rotation of the turbine, means that expectations based on the behaviour of purely pitching airfoils no longer strictly hold. It remains to be seen what the effect of this \( \lambda \)-related velocity modulation is, and how it interplays with the effect of the local angle of attack variation.

It must be recognised that the angle of attack variation and azimuthal phase change are not synonymous, but that the local angle of attack of each blade is a function of both azimuthal angle and tip speed ratio. This variation is illustrated for one cycle in figure 1(top). The relationship between angle of attack, tip speed ratio, and azimuthal angle can be derived as

\[
a_{\text{relative}} = \arctan \left( \frac{\sin \theta}{\lambda + \cos \theta} \right) \quad (3)
\]

Of note is that the pitch-up and pitch-down parts of the cycle are not symmetric. The kinematic asymmetry, coupled with the already low dimensionless pitching rate of the blades, suggests that the stall during the pitch-up phase will be less severe and more likely to exhibit more “quasi-steady” behaviour. It is this part of the cycle which has been measured in the present study.

The mean velocity experienced by each blade is equal to the tangential velocity, \( R \Omega \), with the cyclic variations being due to the change in orientation relative to the freestream, as

\[
U_{\text{relative}} / U_\infty = \sqrt{1 + 2 \lambda \cos \theta + \lambda^2} \quad (4)
\]

This is illustrated in figure 1(bottom). With increasing tip speed ratio, the relative contribution of the tangential blade velocity grows, thus reducing the size of the excursions from the mean of both relative velocity and angle of attack. The blade tangential velocity is an appropriate choice for the reference velocity when concerned with blade aerodynamics and is used to define the

\[
Re = \frac{R \Omega c}{v} \quad (5)
\]

Experiment

Apparatus

A giromill H-type wind turbine with NACA0015 blade section is placed in the three by two foot wind tunnel at Princeton University (figure 2(top)). The turbine blades are of span 450mm, have chord lengths ranging from \( c = 50 \text{mm} \) to \( c = 100 \text{mm} \) and are constructed of aluminium and carbon fibre. Rotor induction, and blade-wake interaction, are minimised by restricting the turbine configuration to two blades only and low solidity.

Measurements on and above the suction surface of the turbine blades are conducted by stereoscopic particle image velocimetry (SPIV), with mineral oil seeding particle size of approximately 1 \( \mu \text{m} \) provided by an MDG brand clean nitrogen fed fog machine. Phase-locked measurements are conducted using two 2560 \( \times \) 2160 pixel sCMOS double shutter cameras, fitted with 50mm focal length lenses, over a region of interest of approximately two blade chord lengths by 1.5. The cameras are mounted suspended above the tunnel on a tuntable axisymmetric with the turbine to allow for measurements to be taken in blade-coordinates at arbitrary azimuthal angles. Figure 2(bottom) represents a schematic view from above the turbine, marking some relevant parameters and the coordinate system. An approximate representative PIV measurement domain is also shown.

Parametric Conditions

The Reynolds number is set equal to 70,000, matching data presented by Ferreira et al [5], but by varying the chord length the effect of dimensionless pitching rate can be isolated from that of the tip speed ratio. Tip speed ratios between \( \lambda = 1 \) and \( \lambda = 5 \) are considered, with blade chord lengths of \( c = 50, 75, \) and 100mm, relating to a dimensionless pitching rate of \( K_p = 0.10, 0.15, \) and 0.20, respectively. The turbine is rotated at an angular velocity, \( \Omega \), of 43, 60, and 90 radians per second, depending on chord length, and the tip speed ratio is set by varying the freestream velocity, \( U_\infty \), between approximately 4.5 and 16m/s. Measurements of the dynamic stall process are taken at between \( \theta = 30^\circ \) and \( \theta = 165^\circ \), in \( 15^\circ \) increments, encompassing angles of attack between \( \alpha = 5.83^\circ \) and \( \alpha = 52.5^\circ \) (figure 3). The parameters explored are listed in table 1.

![Figure 1: Azimuthal variation of the local angle of attack (top), and local relative velocity (bottom), experienced by each turbine blade, and variation with tip speed ratio indicated. Angular units expressed in degrees.](image1)

![Figure 2: Vertical axis wind turbine apparatus mounted in wind tunnel test facility (top), and representation of the vertical axis turbine (as viewed from above), indicating representative measurement domain, coordinate system, and geometric parameters (bottom). Data are taken for \( 30^\circ \leq \theta \leq 135^\circ \).](image2)
PIV Analysis

Image pairs are pretreated via a high-pass filter and the minimum intensity across the ensemble is subtracted. Residual reflections from the blade surface are removed via a masking filter. Cross-correlation PIV is performed on a multi-resolution grid, with initial and final resolution of $64 \times 64$ pixels and $24 \times 24$ pixels, respectively, yielding a spatial resolution of approximately 0.7 mm per vector, or between 0.7% and 1.4% of chord, with 1000 velocity fields acquired at each parametric condition and azimuthal phase.

Vectors are validated against a maximum particle displacement constraint, and a normalised local median filter is applied. On average approximately 1% of vectors are rejected, and these are replaced via mean vector interpolation with nearest neighbours.

Results and Discussion

Strong dynamic stall vortex shedding is observed across a range of conditions. Figure 4 illustrates the flow separation structure at a single phase ($\theta = 90^\circ$) via contours of phase-averaged spanwise vorticity and velocity vectors in the frame of the moving blade. The three figures relate to tip speed ratios of $\lambda = 1, 2, 3$ from left to right, respectively. It is observed that flow separation from the leading edge occurs significantly earlier in each cycle at lower tip speed ratios, consistent with the more rapid increase in the effective angle of attack of the blade, while at higher tip speed ratios the onset of stall is delayed. Figure 4 thus depicts three quite distinct phases of the dynamic stall.

Due to the earlier flow separation, the velocity field at $\lambda = 1$ is circulatory over a large region, with a large leading edge vortex present. At this stage of the stall’s progression the flow has also separated around the trailing edge, forming a trailing edge vortex. Both of these structures continue to be fed circulation from their points of origin via strong shear layers. Of note is the small region of positive vorticity between the airfoil’s upper surface and the leading edge vortex. This is a result of the interaction of the leading edge vortex with the no-slip condition at the airfoil’s surface. This secondary vorticity has been observed experimentally in pitching and impulsively started airfoil studies [3, 6] but never noted in the literature, to the authors’ knowledge, in measurements of vertical axis wind turbine blades.

Conversely, at $\lambda = 3$, no clear leading edge separation has occurred and the flow over the airfoil looks much like an incipient steady or quasi-steady stall, with marginal separation and thickening of the boundary layer occurring along the length of the upper surface. The $\lambda = 2$ flow presents an intermediate case with a tight leading edge vortex, and only some sign of separation of the boundary layer further downstream. Based on these results it appears that the progression of the dynamic stall at these low pitch rates consists of an initially quasi-steady-like separation from near the trailing edge, followed soon thereafter by sudden separation of the boundary layer at the leading edge and subsequent roll up of the boundary layer into a coherent leading edge vortex, thus forcing reattachment of the boundary layer downstream of this vortex until separation at the trailing edge and the formation of a trailing edge vortex.

Figure 5(top) shows the evolution of the average circulation in the leading edge vortex as a function of blade azimuthal angle, for several pitching rates and tip speed ratios. At this stage the data processing is not sufficiently advanced to observe clear trends for $K_c = 0.10$ and 0.20 cases, but delayed onset and development of stall with increased tip speed ratio is evident in the $K_c = 0.15$ data. The usual scaling of circulation, with chord length and freestream velocity,

$$\hat{\Gamma} = \frac{\Gamma}{c U_\infty}$$  \hspace{1cm} (6)

collapses the $K_c = 0.15$ data well (figure 5(bottom)) if also phase-shifted to account for variation in dynamic stall onset angle.

Figure 3: Conditions for which PIV measurements were taken. Angular units expressed in degrees.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Re$</td>
<td>70,000</td>
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<tr>
<td>$\lambda$</td>
<td>1, 2, 3, 3.5, 4, 4.5, 5</td>
</tr>
<tr>
<td>$c$</td>
<td>50, 75, 100 mm</td>
</tr>
<tr>
<td>$K_c$</td>
<td>0.10, 0.15, 0.20</td>
</tr>
<tr>
<td>$\theta$</td>
<td>$30^\circ$–$165^\circ$</td>
</tr>
</tbody>
</table>

Table 1: Experimental parameters.

Figure 4: Phase-averaged vorticity contours and vector fields in the vicinity of a NACA0015 vertical axis wind turbine blade, at a $Re = 70,000$, $\theta = 90^\circ$, and dimensionless pitch rate $K_c = 0.15$. Left: $\lambda = 1$, Middle: $\lambda = 2$, Right: $\lambda = 3$. 
The effect of dimensionless pitch rate, $K_c$, is more nuanced. Figure 6 illustrates selected vorticity fields, all relating to a tip speed ratio of $\lambda = 2$ and azimuthal angle of $\theta = 105^\circ$, but with increasing dimensionless pitch rate from left to right. With greater pitch rate, the leading edge vortex system is seen to inhabit a smaller spatial extent, relative to the chord length. At low pitch rate, $K_c = 0.10$, a significant difference in stall topology is observed. The dynamic stall vortex pinches off from the leading edge earlier at the lower pitch rates, due to the closer mutual proximity and enhanced interaction between the leading and trailing edge vortices.

**Concluding Remarks**

The distinction between the roles of tip speed ratio and dimensionless pitching rate in governing the aerodynamics of wind turbines has been explored. There exist some notable distinctions between the behaviour induced by variation of each. The tip speed ratio is a measure of the relative importance of the blade tangential velocity to the freestream velocity, and has a significant effect on the azimuthal position at which a leading edge dynamic stall vortex first forms on the turbine blade. The rate at which circulation is added to the leading edge vortex once dynamic stall has begun scales with the chord and the freestream velocity for any given dimensionless pitching rate, but the data available at the time of publication are insufficient to draw conclusions as to the scaling behaviour of circulation production across a dimensionless pitching rates. The results do suggest however that the primary effect of variation in dimensionless pitching rate is in the spatial extent of the dynamic stall vortex system relative to the blade chord, thus significantly affecting the late-stage leading edge vortex pinch-off behaviour. A lower dimensionless pitching rate increases the interaction strength between leading and trailing edge vortices and induces an earlier pinch-off. This is expected to have significant implications for the force-generation behaviour of the turbine blades, and in turn the turbine efficiency.

**Acknowledgements**

This research is supported by the Australian-American Fulbright Commission.

**References**


