Vertical axis wind turbines

Aerodynamic challenges to be tackled

Laurent BEAUDET
Institut PPRIME - Université de Poitiers
Outline

- Aerodynamic obstacles to the design of a VAWT
  - How a VAWT works
  - Questioning about the ideal geometry
  - Why it is difficult to study

- Flow curvature
  - What it is
  - What it causes

- Dynamic stall
  - Why it is specific
  - Experimental study of the phenomenon and its consequences
  - Usual numerical models for dynamic stall
Outline

• Aerodynamic obstacles to the design of a VAWT
  • How a VAWT works
  • Questioning about the ideal geometry
  • Why it is difficult to study

• Flow curvature
  • What it is
  • What it causes

• Dynamic stall
  • Why it is specific
  • Experimental study of the phenomenon and its consequences
  • Usual numerical models for dynamic stall
Outline

• Aerodynamic obstacles to the design of a VAWT
  • How a VAWT works
  • Questioning about the ideal geometry
  • Why it is difficult to study

• Flow curvature
  • What it is
  • What it causes

• Dynamic stall
  • Why it is specific
  • Experimental study of the phenomenon and its consequences
  • Usual numerical models for dynamic stall
Aerodynamic obstacles to the design of a VAWT
How does it work?

- Cyclic variation of the angle of attack ($\alpha$)

Sectional view

Freestream velocity
Rotational velocity
Relative velocity

Airfoil’s reference frame

Outer side
Inner side

TSR $\lambda = 2$
How does it work?

- Cyclic variation of the tangential force ($F_t$)
Effect of tip-speed ratio (TSR)

Stall phenomenon

Low angle of attack and increased effect of drag

Power Coefficient ($C_p$) [%]

Tip-Speed Ratio (TSR, $\lambda$)
What are the current trends?

Deepwind
www.deepwind.eu
(Scientific project
DTU/MARIN/
DUWIND/NREL/
MARINTEK/etc...)

Gwind
www.gwind.no
(Gwind)

INFLOW
www.inflow-fp7.eu
(Nenuphar/Technip/
EDF-EN/etc...)

Spinfloat
www.spinfloat.com
(EOLFI, subsidiary of
ASAH LM)

VertaxWind
vertexwind.com
(VertaxWind Ltd, subsidiary of Eurowind Developments)

10th EAWE PhD Seminar on Wind Energy in Europe
October 28-31, 2014 in Orléans, France
What are the current trends?

Deepwind
www.deepwind.eu
(Scientific project DTU/MARIN/DUWIND/NREL/MARINTEK/etc...)

Gwind
www.gwind.no
(Gwind)

INFLOW
www.inflow-fp7.eu
(Nenuphar/Technip/EDF-EN/etc...)

Spinfloat
www.spinfloat.com
(EOLFI, subsidiary of ASAH LM)

VertaxWind
vertaxwind.com
(VertaxWind Ltd, subsidiary of Eurowind Developments)
What are the current trends?

Deepwind  
www.deepwind.eu  
(Scientific project  
DTU/MARIN/  
DUWIND/NREL/  
MARINTEK/etc…)

Gwind  
www.gwind.no  
(Gwind)

INFLOW  
www.inflow-fp7.eu  
(Nenuphar/Technip/  
EDF-EN/etc…)

Spinfloat  
www.spinfloat.com  
(EOLFI, subsidiary of  
ASAH LM)

VertaxWind  
vertexwind.com  
(VertaxWind Ltd,  
subsidiary of Eurowind Developments)

Large blades

Thin blades

10th Eawe PhD Seminar on Wind Energy in Europe  
October 28-31, 2014 in Orléans, France
Optimum?
Optimum?

• Not only a question of aerodynamics...
Optimum?

• Not only a question of aerodynamics...

• Anyway, do we know a kind of "optimal geometry in terms of aerodynamics"?
Optimum?

• Not only a question of aerodynamics...
• Anyway, do we know a kind of "optimal geometry in terms of aerodynamics"?
  • Not sure... To date, no optimal VAWT geometry (or even nearly optimal) seems to exist as attests the large disparities between the geometries.
Optimum?

• Not only a question of aerodynamics...

• Anyway, do we know a kind of "optimal geometry in terms of aerodynamics"?
  • Not sure... To date, no optimal VAWT geometry (or even nearly optimal) seems to exist as attests the large disparities between the geometries

• Reasons?
  • Trade-off resulting from the ranking of the priorities and from the technical choices and requirements (structural strength, safety devices, noise emission, price...)
Optimum?

• Not only a question of aerodynamics...

• Anyway, do we know a kind of "optimal geometry in terms of aerodynamics"?
  • Not sure... To date, no optimal VAWT geometry (or even nearly optimal) seems to exist as attests the large disparities between the geometries

• Reasons?
  • Trade-off resulting from the ranking of the priorities and from the technical choices and requirements (structural strength, safety devices, noise emission, price...)
  • Difficulties to apprehend and model the VAWTs aerodynamics (questionable performance computations and hard and doubtful operation of optimization)
e.g. effect of solidity ($\sigma$)

From Shiono et al. (2000) on a water turbine

Increasing solidity

$$\sigma = \frac{N_{ch}}{S} \left( = \frac{N_c}{2R} \right)$$
e.g. effect of solidity ($\sigma$)
e.g. effect of solidity ($\sigma$)

$$\frac{1}{\lambda_{\text{opt}}^2}$$
e.g. choice of the airfoil section

- Symmetrical or cambered?
  - Most usual: NACA0015, NACA0018
e.g. choice of the airfoil section

• Symmetrical or cambered?
  • Most usual: NACA0015, NACA0018
  • Dedicated airfoil sections:
    • Migliore and Fritschen (1982): Transformed NACA63₂-015
    • Klimas (1984), Berg (1990): Sandia NLF family of airfoils
    • Claessens (2006): DU 06-W-200
    • Ragni et al. (2014): DU 12-W-262
e.g. choice of the airfoil section

- Symmetrical or cambered?
  - Most usual: NACA0015, NACA0018
  - Dedicated airfoil sections:
    - *Migliore and Fritschen (1982)*: Transformed NACA63\textsubscript{2}-015
    - *Klimas (1984), Berg (1990)*: Sandia NLF family of airfoils
    - *Claessens (2006)*: DU 06-W-200
    - *Ragni et al. (2014)*: DU 12-W-262

- Preset toe-in and toe-out blade pitch?
- Position of the mounting point (pitching axis)?
e.g. choice of the airfoil section

- C.J.S. Ferreira (2009): “Varying the pitching axis location and blade camber does not significantly affect the energy conversion in 2D potential flow.”
e.g. choice of the airfoil section

- C.J.S. Ferreira (2009): “Varying the pitching axis location and blade camber does not significantly affect the energy conversion in 2D potential flow.”

“Howevr, it significatly affects the loading on the blades, transferring torque between the upwind and downwind blade passages and changing the average normal force.”
e.g. choice of the airfoil section

- C.J.S. Ferreira (2009): “Varying the pitching axis location and blade camber does affect the performance in 3D potential flow.”
e.g. choice of the airfoil section

- **C.J.S. Ferreira (2009)**: “Varying the pitching axis location and blade camber *does affect the performance in 3D potential flow.*”

“We identified a large design space with significant improvements to be achieved. Research on cambered aerofoils and pitching axis location can lead to substantial gains in the efficiency of VAWT”
What kind of difficulties are raised?

- *Complex aerodynamics at blade, rotor and wind-farm scales*
What kind of difficulties are raised?

- **Complex aerodynamics at blade, rotor and wind-farm scales**
- **Rotor and blade scales:**
  - **Unsteadiness**, variations of the Reynolds number, possible very low flow velocities relative to the airfoil...

![Diagram of aerodynamics](image-url)
What kind of difficulties are raised?

• **Complex aerodynamics at blade, rotor and wind-farm scales**

• **Rotor and blade scales:**
  - *Unsteadiness*, variations of the Reynolds number, possible very low flow velocities relative to the airfoil...
  - **Very vortical flows**
    - Blade-wake interactions
    - Possible dynamic stall

*From C. He (2013)*
What kind of difficulties are raised?

- **Complex aerodynamics at blade, rotor and wind-farm scales**

- **Rotor and blade scales:**
  - *Unsteadiness*, variations of the Reynolds number, possible very low flow velocities relative to the airfoil...
  - *Very vortical flows*
    - Blade-wake interactions
    - Possible dynamic stall
  - *Flow curvature effects*
What kind of difficulties are raised?

- **Complex aerodynamics at blade, rotor and wind-farm scales**
- **Rotor and blade scales:**
  - *Unsteadiness*, variations of the Reynolds number, possible very low flow velocities relative to the airfoil...
  - **Very vortical flows**
    - Blade-wake interactions
    - Possible dynamic stall
  - **Flow curvature effects**
  - **3D effects**
    - Tip vortices
    - Helical blades

*From C. He (2013)*
What is flow curvature?

- Change in the aerodynamic behavior of an airfoil
  *induced by its own motion*
What is flow curvature?

- Change in the aerodynamic behavior of an airfoil \textit{induced by its own motion}.
- Decomposition of the motion.
What is flow curvature?

- Change in the aerodynamic behavior of an airfoil induced by its own motion
- Decomposition of the motion
Effect of rotation
Effect of rotation

- Velocity deflection induced by the airfoil’s rotation

\[ V(x) = \dot{\alpha}(x-x_0) \]
Effect of rotation

- Relative velocity varies along the airfoil’s chord
Effect of rotation

• So the angle of attack varies too...
Effect of rotation

- It behaves like a virtual cambered airfoil in a uniform flow field
Effect of rotation

- It generates lift due to its virtual characteristics

\[ C_L = 2\pi \frac{\dot{\alpha}}{U_\infty} \left( \frac{3}{4} \frac{c-x_0}{c} \right) \]

See Y.C. Fung (1955)
Effect of rotation

• So the rotating airfoil generates lift by its own motion

\[ C_L = 2\pi \frac{\dot{\alpha}}{U_\infty} \left( \frac{3}{4} c - x_0 \right) \]

\[ C_L = 2\pi \alpha_{eq} \text{ where } \alpha_{eq} = \alpha_x = 3/4c \]

See Y.C. Fung (1955)
Effect of translation

- Translation \textit{perpendicular to} $U_\infty$

\[ C_L = 2\pi \alpha_{eq} \text{ where } \alpha_{eq} = \alpha_x = 3/4c \]
Effect of translation

- **Translation perpendicular to** $U_\infty$

- **Translation parallel to** $U_\infty$
  - Make the magnitude of the relative velocity change over time

\[ C_L = 2\pi \alpha_{eq} \quad \text{where} \quad \alpha_{eq} = \alpha_x = 3/4c \]
Flow curvature in a VAWT

• Combined effects of rotation and translation
Flow curvature in a VAWT

- Combined effects of rotation and translation

\[ F(Z) = -Z_n \ln \left( \frac{Z_n - Z}{Z_n} \right) \text{ where } W(Z_n) = 0 \]
Flow curvature in a VAWT

• Combined effects of rotation and translation

\[ F(Z) = -Z_n \ln \left( \frac{Z_n - Z}{Z_n} \right) \text{ where } W(Z_n) = 0 \]
How to define an angle of attack?

• Angle between the chord line and the *vector representing the upstream relative velocity (without considering deflections by its own wake)*
How to define an angle of attack?

- Angle between the chord line and the vector representing the upstream relative velocity (without considering deflections by its own wake)
  - Where is this upstream relative vector?
How to define an angle of attack?

• Angle between the chord line and the vector representing the upstream relative velocity (without considering deflections by its own wake)

• Where is this upstream relative vector?
• Can one find an unperturbed velocity at blade scale?

From C. He (2013)
How to define an angle of attack?

• Angle between the chord line and the vector representing the upstream relative velocity (without considering deflections by its own wake)
  • Where is this upstream relative vector?
  • Can one find an unperturbed velocity at blade scale?

• Many points of view depending on the author

From C. He (2013)
How to define an angle of attack?

- Angle between the chord line and the vector representing the upstream relative velocity (without considering deflections by its own wake)
  - Where is this upstream relative vector?
  - Can one find an unperturbed velocity at blade scale?

- Many points of view depending on the author

- Why to calculate it?
  - For its use in all actuator point/line models and in all dynamic stall models

From C. He (2013)
Some hints and remarks

- It is emphasized by the *chord-to-radius ratio*
Some hints and remarks

• It is emphasized by the *chord-to-radius ratio*

• Use the angle of attack at $\frac{3}{4}$ of the chord line
  • Takes into account some flow curvature effects
Some hints and remarks

• It is emphasized by the \textit{chord-to-radius ratio}

• Use the angle of attack at \( \frac{3}{4} \text{ of the chord line} \)
  • Takes into account some flow curvature effects

• Remove the velocity induced by the \textit{near wake}
Some hints and remarks

- It is emphasized by the *chord-to-radius ratio*
- Use the angle of attack at $\frac{3}{4}$ of the chord line
  - Takes into account some flow curvature effects
- Remove the velocity induced by the *near wake*
- Add compensation terms in the computation of loads, e.g.
  
  $\Delta C_N \approx -C_L \alpha \left( \frac{3}{4} c - x_m \right) \frac{\omega}{W} \approx -\frac{\pi c \lambda U_\infty}{2RW}$

See D.J. Sharpe (1984)
To go further...

- Analogy with flapping wing
  - D. N. Gorelov (2009), Worasinchai et al. (2012, 2014): “This analogy suggests that unsteadiness could be exploited to generate additional thrust and that this unsteady thrust generation is governed by rotor geometry”
To go further...

• Analogy with flapping wing
  • D. N. Gorelov (2009), Worasinchai et al. (2012, 2014): “This analogy suggests that unsteadiness could be exploited to generate additional thrust and that this unsteady thrust generation is governed by rotor geometry”

• Viscous effects of flow curvature:
  • Additional drag (Hirsch and Mandal (1984))
  • Centrifugal effects boundary layer (Migliore et al. (1980))
  • Impact on boundary layer separation (dynamic stall)
Dynamic stall in a VAWT
What is dynamic stall and in which conditions does it happen?

- **Dynamic stall** is the stall phenomenon associated with the unsteady motion of lifting surfaces at high angles of attack.
What is dynamic stall and in which conditions does it happen?

- **Dynamic stall** is the stall phenomenon associated with the unsteady motion of lifting surfaces at high angles of attack.

![Diagram showing steady and unsteady curves with an arrow indicating delay in boundary layer separation.]

- ![Diagram showing steady and unsteady curves with an arrow indicating delay in boundary layer separation.]

- Delay in boundary layer separation
What is dynamic stall and in which conditions does it happen?

• **Dynamic stall** is the stall phenomenon associated with the **unsteady motion** of lifting surfaces at **high angles of attack**

![Diagram showing suction peak and boundary layer separation](image)

- Delay in boundary layer separation
- Creation of a leading edge vortex (LEV)
What is dynamic stall and in which conditions does it happen?

- **Dynamic stall** is the stall phenomenon associated with the unsteady motion of lifting surfaces at high angles of attack.

  - Delay in boundary layer separation
  - Creation of a leading edge vortex (LEV)
  - Shedding of the LEV

![Diagram showing the behavior of lift coefficient ($C_L$) against angle of attack ($\alpha$)]
What is dynamic stall and in which conditions does it happen?

• *Dynamic stall* is the *stall* phenomenon associated with the *unsteady motion* of lifting surfaces at high angles of attack.

- Delay in boundary layer separation
- Creation of a leading edge vortex (LEV)
- Shedding of the LEV
What is dynamic stall and in which conditions does it happen?

- **Dynamic stall** is the stall phenomenon associated with the unsteady motion of lifting surfaces at high angles of attack.

![Diagram](attachment:image.png)

- Delay in boundary layer separation
- Creation of a leading edge vortex (LEV)
- Shedding of the LEV
- Delay in boundary layer reattachment
What is dynamic stall and in which conditions does it happen?

- **Dynamic stall** is the **stall** phenomenon associated with the **unsteady motion** of lifting surfaces at **high angles of attack**
What is dynamic stall and in which conditions does it happen?

- **Dynamic stall** is the **stall** phenomenon associated with the **unsteady motion** of lifting surfaces at **high angles of attack**.

- When are these conditions met in a VAWT?
  - High angles of attack at **low TSR**.
What is dynamic stall and in which conditions does it happen?

• Dynamic stall is the stall phenomenon associated with the unsteady motion of lifting surfaces at high angles of attack.

• When are these conditions met in a VAWT?
  • High angles of attack at low TSR
  • Flow over a VAWT is unsteady by nature
    • Level of unsteadiness is usually measured with the reduced frequency (k)

\[
k = \frac{\omega_c}{2U_{ref}}
\]
What is dynamic stall and in which conditions does it happen?

• **Dynamic stall** is the stall phenomenon associated with the **unsteady motion** of lifting surfaces at **high angles of attack**

• When are these conditions met in a VAWT?
  • High angles of attack at **low TSR**
  • Flow over a VAWT is unsteady by nature
  • Level of unsteadiness is usually measured with the reduced frequency (k)

\[
k = \frac{\omega c}{2U_{\text{ref}}} = \frac{c}{2R} \left[ (\lambda - 1) \tan \left( \left( \frac{\lambda^2 - 1}{\lambda - 1} \right)^{-1/2} \right) \right]^{-1}
\]

*See Laneville and Vittecoq (1986)*
What is dynamic stall and in which conditions does it happen?

- **Dynamic stall** is the stall phenomenon associated with the *unsteady motion* of lifting surfaces at *high angles of attack*.

When are these conditions met in a VAWT?

- High angles of attack at *low TSR*
- Flow over a VAWT is unsteady by nature
  - Level of unsteadiness is usually measured with the reduced frequency (*k*)
  - *Low TSR and high chord-to-radius ratio* for high unsteadiness
What is dynamic stall and in which conditions does it happen?

- **High chord-to-radius ratio**
  - So high solidity \( \sigma = \frac{N_c}{2R} \)
  - Chosen design for low optimal TSR

![Graph showing optimal TSR vs. solidity](image_url)
What is dynamic stall and in which conditions does it happen?

- **High chord-to-radius ratio**
  - So high solidity \( \sigma = \frac{Nc}{2R} \)
  - Chosen design for low optimal TSR

- **Low TSR** \( \lambda = \frac{R\omega}{U_\infty} \)
  - During usual operation for a high solidity VAWT
  - During start-up \( (\omega \approx 0) \)
  - For stall regulation (prescribed \( \omega \))
Why does dynamic stall in a VAWT differs from a usual one?

• Reference:
  • Sinusoidal pitch in a steady uniform flow
Why does dynamic stall in a VAWT differs from a usual one?

• Reference:
  • Sinusoidal pitch in a steady uniform flow

• Differences:
  • Variation of the angle of attack is not sinusoidal

![Normalized angle of attack vs azimuthal angle](image)
Why does dynamic stall in a VAWT differs from a usual one?

- **Reference:**
  - Sinusoidal pitch in a steady uniform flow

- **Differences:**
  - Variation of the angle of attack is *not sinusoidal*
Why does dynamic stall in a VAWT differs from a usual one?

- **Reference:**
  - Sinusoidal pitch in a steady uniform flow

- **Differences:**
  - Variation of the angle of attack is *not sinusoidal*
    - Not symmetrical
    - Positive and negative high angles of attack
    - Fast and changing pitch rate (high k)
Why does dynamic stall in a VAWT differs from a usual one?

- Reference:
  - Sinusoidal pitch in a steady uniform flow

- Differences:
  - Variation of the angle of attack is *not sinusoidal*

*From R.K. Angell (1990)*
Why does dynamic stall in a VAWT differs from a usual one?

- Reference:
  - Sinusoidal pitch in a steady uniform flow

- Differences:
  - Variation of the angle of attack is not sinusoidal
    - Not symmetrical
    - Positive and negative high angles of attack
    - Fast and changing pitch rate (high k)
      - Modifies the behavior of the boundary layer separation and reattachment

From R.K. Angell (1990)
Why does dynamic stall in a VAWT differs from a usual one?

- Reference:
  - Sinusoidal *pitch* in a steady uniform flow

- Differences:
  - Not only pitch, but also *plunge, fore and aft motions*

*From Laneville et al. (1985)*

*From Favier et al. (1988)*
Why does dynamic stall in a VAWT differs from a usual one?

• Reference:
  • Sinusoidal pitch in a steady uniform flow

• Differences:
  • Not only pitch, but also *plunge, fore and aft motions*
    • Complex combination of synchronized motions
    • Does not seem to change the process, but changes the *triggering and timing* of the elementary steps, and also the *vortex dynamics*
Why does dynamic stall in a VAWT differs from a usual one?

- Reference:
  - Sinusoidal pitch in a **steady uniform** flow

- Differences:
  - *Unsteady and curved flow* relative to the airfoil
    - Variation of the velocity magnitude (up to very low values)
    - Effects of Reynolds number
    - Slow vortex convection
Why does dynamic stall in a VAWT differs from a usual one?

• Reference:
  • Sinusoidal pitch in a **steady uniform** flow

• Differences:
  • *Unsteady and curved flow* relative to the airfoil
    • Variation of the velocity magnitude (up to very low values)
      • Effects of Reynolds number
      • Slow vortex convection
  • Curved flow
    • Unsteadily curved
    • Leads to strong blade-wake interactions
What happens in the rotor?

- Flow visualization in the rotor

2 blades, $c/R \approx 0.33$, $\lambda = 2.14$, $Re_c \approx 6400$

Adapted from Brochier et al. (1986) on a water turbine
What happens in the rotor?

• Flow visualization in the rotor

2 blades, c/R \approx 0.33, \lambda = 2.14, \text{Re}_c \approx 6400

Adapted from Brochier et al. (1986) on a water turbine
What happens in the rotor?

- Flow visualization in the rotor

2 blades, \( c/R \approx 0.33 \), \( \lambda = 2.14 \), \( Re_c \approx 6400 \)

*Adapted from Brochier et al. (1986) on a water turbine*
What happens in the rotor?

- Flow visualization in the rotor

2 blades, $c/R \approx 0.33$, $\lambda = 2.14$, $Re_c \approx 6400$

Adapted from Brochier et al. (1986) on a water turbine
What happens in the rotor?

- Flow visualization in the rotor

2 blades, $c/R \approx 0.33$, $\lambda = 2.14$, $Re_c \approx 6400$

*Adapted from Brochier et al. (1986) on a water turbine*
What happens in the rotor?

- Flow visualization in the rotor

2 blades, $c/R \approx 0.33$, $\lambda = 2.14$, $Re_c \approx 6400$

Adapted from Brochier et al. (1986) on a water turbine
What happens in the rotor?

• Flow visualization in the rotor

$c/R \approx 0.33, \lambda \approx 2$

2 blades, $\text{Re}_c \approx 6400$
Brochier et al. (1986)

1 blade, $\text{Re}_c \approx 1000$
Fujisawa et al. (1995)
What happens in the rotor?

• Particle Image Velocimetry (PIV) near the blade

• Fujisawa et al.
  \( \sigma = 0.167 \) and \( Re_c \approx 1500 \)

• Brochier et al.
  \( \sigma = 0.333 \) and \( Re_c \approx 6400 \)

• J. Bossard
  \( \sigma = 0.550 \) and \( Re_c \approx 1.8 \times 10^5 \)

3 blades, \( c/R \approx 0.37, Re_c \approx 1.8 \times 10^5 \)

Adapted from J. Bossard (2012) on a water turbine
What happens in the rotor?

- Particle Image Velocimetry (PIV) near the blade

3 blades, $c/R \approx 0.37$, $Re_c \approx 1.8 \times 10^5$

Adapted from J. Bossard (2012) on a water turbine
What happens in the rotor?

- Particle Image Velocimetry (PIV) near the blade

3 blades, \(c/R \approx 0.37\), \(Re_c \approx 1.8 \times 10^5\)

Adapted from J. Bossard (2012) on a water turbine
Direct effects

- Consequences:
  - Suction effect of the LEV
  - Boundary layer separation

\[ \lambda = 1, \text{ at } 20\% \text{ of the chord line on the inner side} \]

\[ \text{Pressure coefficient } (c_p) \]

Outer side

Inner side

Adapted from L. Beaudet (2014)

3 blades, \( c/R \approx 0.42, \lambda = 1, \text{Re}_c \approx 1.7 \times 10^5 \)
Direct effects

• Consequences:
  • Suction effect of the LEV
  • Boundary layer separation
  • Blade-vortex interaction

Adapted from L. Beaudet (2014)

3 blades, c/R ≈ 0.42, λ = 1, Re_c ≈ 1.7×10^5
Consequences

• Dynamic stall affects the whole VAWT:
  • *High blade loading* and impact on *fatigue life*
Consequences

• Dynamic stall affects the whole VAWT:
  • *High blade loading* and impact on *fatigue life*
  • Impacts on *torque* and *power* extracted from the wind
Consequences

• Dynamic stall affects the whole VAWT:
  • High blade loading and impact on fatigue life
  • Impacts on torque and power extracted from the wind
  • Interference with the rotor control (passive stall control)

From Sutherland et al. (2012)
Consequences

• Dynamic stall affects the whole VAWT:
  • *High blade loading* and impact on *fatigue life*
  • Impacts on *torque* and *power* extracted from the wind
  • Interference with the *rotor control* (passive stall control)
  • Impacts on the *dynamics of the wake* (wind farm)
Consequences

• Dynamic stall affects the whole VAWT:
  • *High blade loading* and impact on *fatigue life*
  • Impacts on *torque* and *power* extracted from the wind
  • Interference with the *rotor control* (passive stall control)
  • Impacts on the *dynamics of the wake* (wind farm)
  • *Noise emission* (vortices and blade-vortex interaction)
Modeling dynamic stall

• Most used solution: *semi-empirical dynamic stall models* (Gormont, ONERA, Leishman-Beddoes...)
Modeling dynamic stall

- **Most used solution:** *semi-empirical dynamic stall models* (Gormont, ONERA, Leishman-Beddoes...)
  - Consist in *only* calculating *unsteady loads* from the angle of attack and static loads
    - Again, how to choose the angle of attack...
    - Affect loads, but neither pressure distribution nor wake...
Modeling dynamic stall

- **Most used solution:** *semi-empirical dynamic stall models* (Gormont, ONERA, Leishman-Beddoes...)
  - Consist in **only** calculating *unsteady loads* from the angle of attack and static loads
    - Again, how to choose the angle of attack...
    - Affect loads, but neither pressure distribution nor wake...
  - Are based on usual cases of dynamic stall encountered in *aeronautics*
    - Not necessarily adapted to the specificities of VAWT (Mach and Reynolds numbers, type of motion, flow curvature, etc...)
    - Adaptations exist for wind turbines (e.g. *Sheng et al. (2008)*)
Modeling dynamic stall

• Other options:
  • CFD...

PIV (experimental)  LES (numerical)

From C.J.S. Ferreira (2009)

1 blade, c/R ≈ 0.25, λ = 2, Re_c ≈ 5×10^4
Modeling dynamic stall

• Other options:
  • CFD...
  • Double-wake model (Zanon et al. (2014))
Modeling dynamic stall

- Other options:
  - CFD...
  - Double-wake model (Zanon et al. (2014))

Classical 1-wake panel method

*Adapted from Riziotis and Voutsinas (2008)*
Modeling dynamic stall

- Other options:
  - CFD...
  - Double-wake model *(Zanon et al. (2014))*

Diagram:

Classical 1-wake panel method

*Adapted from Riziotis and Voutsinas (2008)*

Double-wake model

Wake originating from the separation point
Modeling dynamic stall

- Other options:
  - CFD...
  - Double-wake model (Zanon et al. (2014))

Classical 1-wake panel method

\[ \text{Double-wake model} \]

From Zanon et al. (2014)

1 blade, \( c/R \approx 0.25, \lambda = 2, \text{Re}_c \approx 5 \times 10^4 \)
Control of dynamic stall on a VAWT

- Methods already tested or studied on a VAWT:
  - Vortex generators (VGs)
    - Sutherland et al. (2012) about tests conducted in the 80ies: “We equipped the Test Bed with vortex generators (...). The results were quite disappointing, as we were not able to detect any significant difference in turbine performance due to the presence of the VGs.”
Control of dynamic stall on a VAWT

• Methods already tested or studied on a VAWT:
  • Vortex generators (VGs)
  • Active or passive pitch control
    • B.K. Kirke (1998), Staelens et al. (2003), etc...
  • Flap deflection
    • D. Rathi (2012) (numerical simulations only)
Control of dynamic stall on a VAWT

- Methods already tested or studied on a VAWT:
  - Vortex generators (VGs)
  - Active or passive pitch control
  - Flap deflection
  - Synthetic jets (steady/unsteady in/out air jets)
  - Plasma actuators
    - Greenblatt et al. (2012, 2014)
Aerodynamic challenges to be tackled

1. Better understanding of the physical processes of the aerodynamic phenomena and assessment of their effects at different scales

   - Flow curvature, dynamic stall, 3D effects, wake development, aeroelasticity, etc...
Aerodynamic challenges to be tackled

1. Better *understanding of the physical processes* of the aerodynamic phenomena and *assessment of their effects* at different scales
   - Flow curvature, dynamic stall, 3D effects, wake development, aeroelasticity, etc...

2. *Modeling* of these phenomena
   - CFD, vortex models, semi-empirical dynamic stall models, etc...
Aerodynamic challenges to be tackled

1. Better understanding of the physical processes of the aerodynamic phenomena and assessment of their effects at different scales
   - Flow curvature, dynamic stall, 3D effects, wake development, aeroelasticity, etc...

2. Modeling of these phenomena
   - CFD, vortex models, semi-empirical dynamic stall models, etc...

3. Adaptation of numerical tools to optimize VAWT’s geometry or to control the effects of the aerodynamic phenomena with actuation
Any question?
• South, P. & Rangi, R. S., A Wind Tunnel Investigation of a 14ft. Diameter Vertical Axis Windmill, National Research Council (NRC), Laboratory technical report LTR-LA-105, National Aeronautical Establishment, 1972

• Mays, I. D., The Development Of The Variable Geometry Vertical Axis Wind Turbine, PhD thesis, University of Reading, 1979


• Armstrong, S., Power performance, flow behaviour and excitation response of canted blades for a vertical axis wind turbine, Master thesis, McMaster University, Mechanical Engineering Department, 2011

References (2/6)

- Bossard, J., Caractérisation expérimentale du décrochage dynamique dans les hydroliennes à flux transverse par la technique de vélocimétrie par image de particules (PIV) - Comparaison avec les résultats issus des simulations numériques, PhD thesis, *Université de Grenoble, Laboratoire des Ecoulements Géophysiques et Industriels (LEGI)*, 2012
References (3/6)

• Ferreira, C. J. S., The near wake of the VAWT 2D and 3D views of the VAWT aerodynamics, PhD thesis, Delft University of Technology, Faculty of Aerospace Engineering, 2009
• He, C., Wake Dynamics Study of an H-type Vertical Axis Wind Turbine, Master thesis, Delft University of Technology, Faculty of Aerospace Engineering, 2013
• Sharpe, D. J., Refinements and developments of the multiple streamtube theory for the aerodynamic performance of vertical axis wind turbines, 6th BWEA Wind Energy Conference, 1984, pp. 148 - 159
• Hirsch, C. & Mandal, A. C., Flow curvature effect on vertical axis Darrieus wind turbine having high chord-radius ratio, European Wind Energy Conference (EWEC), 1984, pp. 405 - 410

• Angell, R. K., An Experimental Investigation Into The Dynamic Suitability Of Thick Section Aerofoils For The Blades Of Large Scale Vertical Axis Wind Turbines PhD thesis, *University of Reading*, 1990


References (5/6)

• Beaudet, L., Etude expérimentale et numérique du décrochage dynamique sur une éolienne à axe vertical de forte solidité, PhD thesis, Université de Poitiers, 2014
• Kirke, B. K., Evaluation of self-starting VAWT for stand-alone applications, PhD thesis, Griffith University, School of Engineering, 1998
References (6/6)