The Design Challenges of Large, Deep-Water, Vertical-Axis Wind Turbine Rotors

Josh Paquette

Sandia National Laboratories
Overview

- Sandia VAWT Experience
- VAWT Potential for Deep-Water Offshore Wind
- Sandia Offshore Technology Development Project
  - VAWT Airfoils
  - Aerodynamic Modeling
  - Aeroelastic Modeling
- Scaling to Large Machines
  - Design Options
  - Mass Properties of 5MW Darrieus Glass Rotors
  - Structural Dynamics Concerns
  - Parked Loads
Sandia VAWT Experience
Previous SNL VAWT Research

- Early 1970’s to mid 1990’s
- Started with Savonius rotors, Moved Quickly to Full-Darrieus Rotors
- Succession of Designs: Leading to the Very Successful 17-m, 100 kW Full-Darrieus VAWT
  - Successful Commercialization
    - Several US Manufactures
    - FloWind
      - Over 500 VAWTs Deployed: Primarily in Altamont Pass
      - 170 19-m Turbines in their Fleet
- Culminated with Design of the 34-m Research VAWT Test Bed
  - Commercialization
    - The Point Design
    - FloWind EHD Turbine
34-m VAWT Test Bed

- Located in Bushland, TX
  - Dedicated: May, 1988
  - Decommissioned: Spring, 1998
- Rotor: 34-m Dia, 50-m Height
- Performance:
  - Variable Speed: 25 to 38 rpm
  - Rated Power: 500 kW
- Heavily Instrumented
  - 72 Strain, 25 Environmental,
  - 22 Performance, 29 Electrical
- Large Database, Many Publications
Tower was the Largest Cost Element of the Rotor
Cantilever Designs

- **“H” Rotor**
  - No Reefing Capabilities
  - High Performance Penalty
    - Blade-to-Cross-Arm
    - Tip Losses
  - Aerodynamics Brakes in the Cross Arm

- **“Y”, “V” or Sunflower Rotor**
  - Blade Tip Stabilization: Aerodynamic Losses
  - Foldable Design
    - High Wind Survival
    - Hinged Blades: Maintenance Problem

- **Molded Composite Blades**
Long Blades
- Twice as Long as Equivalent HAWT Blade
- Innovative Materials & Manufacturing Techniques

Active Aerodynamic Control
- Passive Power Control: SNF Airfoils
- Aerodynamic Brakes

Large Footprint: Guy System
- Cantilever Designs

Torque Ripple
- Compliant Drive Train

Power Train
- May or May Not Self Start: Starting System Required
- Right-Angle Transmission
Considerations for Off-Shore Applications

- **Aerodynamics**
  - SNL NLF Airfoils, Summer Airfoils
  - Better Structural Characteristics: “Thick Airfoil” Series
  - Eliminate and/or Fair Struts and Joints

- **Blade Materials**
  - Composite Materials
  - Molded Composite Structure
    - High Bend-in-Place Stresses
    - Tailored Chord Distribution

- **Drive Train and Power Components**
  - Variable Speed with Regenerative Braking
  - Brake System
  - Direct-Drive
  - Vertically Mounted Generators
VAWT Potential for Deep-Water Offshore Wind
Offshore Wind Project Cost Breakdown

- Turbine: 28%
- Support Structure: 13%
- Logistics and Installation: 10%
- Electrical Infrastructure: 11%
- O&M: 21%
- Other Variable Costs: 11%
- Development & Permits: 5%
- Other Capital Costs: 1%

Musial & Ram 2010
Offshore Design Challenge: O&M Costs > 25% of the Total Project Cost

Drivetrain at tower top

Drivetrain at tower base

Horizontal Axis Wind Turbine (HAWT)

Outcome: Larger O&M cost

Vertical Axis Wind Turbine (VAWT)

Outcome: Smaller O&M cost

No yaw and blade pitch systems

Yaw and blade pitch systems add complexity
Offshore Design Challenge: Foundation Costs > 20% of Total Project Cost

Outcome:
Relatively expensive platform, mooring, and foundation

Higher CG

Horizontal Axis Wind Turbine (HAWT)

Outcome:
Relatively inexpensive platform, mooring, and foundation

Lower CG

Vertical Axis Wind Turbine (VAWT)

Outcome:
Relatively inexpensive platform, mooring, and foundation
Operating cyclical gravity loads and resulting fatigue impact increase with rotor size.

**Outcome:**
- Blade weight becomes increasingly difficult design challenge with larger rotors.
- Operating cyclical gravity loads and resulting fatigue impact are minimal.

**Horizontal Axis Wind Turbine (HAWT)**

**Vertical Axis Wind Turbine (VAWT)**

**Offshore Design Challenge:**

- Increased Supporting Infrastructure Cost
- Demand Larger Rotors

**Outcome:**
- Blade weight does not limit rotor size.
Wind direction can vary significantly across a large rotor, which attempts to align with the wind.

**Outcome:** Rotor performance decreases with size

VAWT rotor energy capture is insensitive to wind direction.

**Outcome:** Rotor performance insensitive to size

---

**Offshore Design Challenge:**

*Increased Supporting Infrastructure Cost Demand Larger Rotors*

**Horizontal Axis Wind Turbine (HAWT)**

**Vertical Axis Wind Turbine (VAWT)**
Sandia Offshore Technology Development Project
Demonstrate the feasibility of the Vertical-Axis Wind Turbine (VAWT) architecture for very large-scale deployment in the offshore environment.

The most critical barrier to offshore wind, high Cost of Energy (COE), is specifically targeted with the overall goal of achieving a 20% reduction in COE through application of VAWT rotor technology.
Key idea: Aerodynamic optimum for a VAWT airfoil is lift curve slope / drag, not lift / drag

- Consequence of the inherently unsteady nature of VAWT aerodynamics
- Leads to thicker optimal foils
- Thicker foils give stiffer blades

TU Delft has designed a new family of thick VAWT airfoils

SNL is assessing the performance under soiled conditions using CFD

Goal: incorporation into SNL VAWT rotor designs
**VAWT Aerodynamic Modeling (TU Delft)**

- **Goal:** Develop a highly accurate, but efficient, code for VAWT aerodynamics
- **Approach:** Hybrid Eulerian/Lagrangian Method
  - The flow in the near-blade region is calculated using conventional CFD
  - The flow in the wake is calculated using a vortex particle method
- **Accomplishments**
  - 2D version of the code is complete and is undergoing testing
- **Future Work**
  - Extension to 3D
  - Validation against VAWT experimental data
  - Efficiency improvements on GPU computers
Offshore Wind Energy Simulation Toolkit for Vertical-axis Wind Turbines (VAWTs)

- **Features:**
  - Considers VAWTs of arbitrary configuration
  - Enables modal and transient analysis capabilities
    - Resonance / stability
    - Turbulent winds, start up, shut down, etc.
  - Enables couplings/interfaces to:
    - Arbitrary aerodynamics modules
    - Arbitrary hydrodynamics/mooring modules
    - Floating platform motions
    - Generator and drivetrain dynamics
    - Turbine control algorithms
  - Accounts for passive aeroelastic couplings
  - Open-source, batch capability

- **Validation (SNL 34-meter VAWT)**
  - *Campbell diagram:*

- **Arbitrary VAWT Geometries:**

- **SNL 34-m parked mode shapes:**
  - 1st Antisymmetric Flatwise
  - 1st Symmetric Flatwise
  - 1st Propeller
  - 1st Blade Edgewise (Butterfly)
  - 2nd Antisymmetric Flatwise
  - 2nd Symmetric Flatwise
Scaling to Large Machines
Design Options

- 2-Bladed vs. 3-Bladed
  - Generally, 2 bladed should be lighter
  - 3 bladed rotor is balanced and reduces torque ripple

- Double Tapered vs. Single Tapered vs. Non-Tapered (constant chord)
  - Aerodynamically Optimal vs. Low CG vs. Ease of Manufacturing

- Straight vs. Tapered Tower

- Glass vs. Carbon
  - Cost vs. Weight

- Darrieus vs. V-Shaped
  - Structurally and Aerodynamically Efficient vs. Low Rotor Weight
5MW Scaling of Glass Darrieus: Effect of Design Options on Rotor Mass
5MW Scaling of Glass Darrieus: Effect of Design Options on Rotor CG
Double Tapered Blades

2-Bladed

3-Bladed

Frequency (Hz)

Rotor Speed (RPM)

Straight Tower

Tapered Tower
Single Tapered Blades

2-Bladed

3-Bladed

Straight Tower

Tapered Tower
Non-Tapered Blades

2-Bladed

3-Bladed

Straight Tower

Tapered Tower
Surface Strains for Parked, 3-Bladed, Glass, Single-Tapered 5MW Darrieus Rotor