Variable Geometry Wind Turbine Technologies for Performance Enhancement, Improved Survivability and Reduced Cost of Energy

Glen Whitehouse, Robert McKillip, Todd Quackenbush, Marc Sibilia and Alan Bilanin
Continuum Dynamics, Inc., Ewing, NJ

and

Paul Veers
National Renewable Energy Laboratory, Golden, CO

Presented at the
2013 North American Wind Energy Academy Symposium
August 7th 2013

Continuum Dynamics, Inc.

Overview of the Presentation

- **Motivation and Background**
- **Variable Geometry HAWT**
  - Deformable trailing edge system
  - Concept
  - Performance
- **Variable Geometry VAWT**
  - VAWT overview
  - VG concept
  - Performance
  - Additional design considerations
- **Conclusions**

Horns Rev offshore wind farm

Lillgrund offshore wind farm

Images courtesy of Vattenfall and Siemens

Motivation and Background

Motivation and Background

- **Improvements to wind turbine technology are required if they are to become lowest Cost of Energy (COE) power source**
  - Efficiency
  - Reliability
- **Active/adaptive structures and controls can have a significant impact**
  - Minimize extreme loads
  - Smooth vibratory loads (i.e. reduce fatigue)
  - Optimize in-situ performance
- **Approaches must be light-weight and low cost**
  - New turbine design
  - New blade design
  - Retrofit (turbine life extension?)

Turbines undergoing testing at NWTC

Motivation and Background (cont'd)

- **Wind turbine structures are designed to survive extreme loads**
  - Passive approaches
    - Adding structural mass
    - Aeroelastic tailoring
    - Indirect yaw control
  - Active approaches
    - Direct yaw control
    - Variable pitch (collective, cyclic, individual blade control, higher harmonic control)
    - Variable speed
    - Blade-mounted control surfaces (flaps, slats, VGs etc.)

- **Key issue with all approaches is cost**
  - Direct: cost of implementation/devices
  - Indirect cost: weight
  - For example, blade mounted control effectors
    - Hydraulic actuators are low risk, but are large, heavy and require significant system modifications
    - Electric actuators may require fewer system modifications, but are still large and heavy

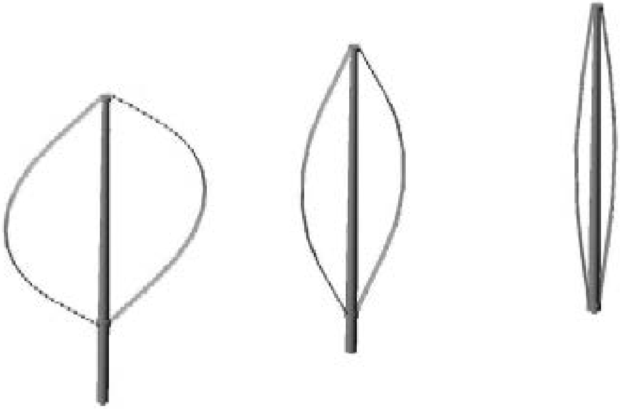
SANDIA SMART blade

Motivation and Background (cont'd)

- **Variable geometry may be able to significantly reduce COE**
  - Performance optimization
    - As a function of wind conditions and in situ effects
  - Reduction of vibratory loads (fatigue)
    - Life extension
    - Possible reduced mass
  - Storm load mitigation
    - Possible reduced mass
  - Tradeoff is complexity

- **Two approaches to variable geometry active control presented**
  - Variable geometry HAWT
    - Low-cost, low-footprint unconventional approach
    - Proof-of-concept numerical and experimental study
    - Deformable trailing edge blades
    - Retrofittable and low cost
  - Variable geometry VAWT
    - Paper design study with proof-of-concept numerical and wind tunnel results
    - Offshore application
    - Flexible blades that furl

Deformable HAWT blade trailing edge



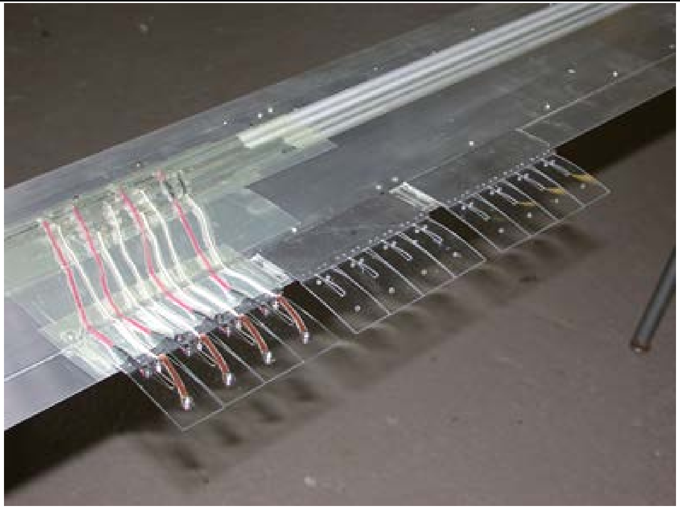
Schematic of VG-VAWT

Variable Geometry
Horizontal Axis Wind Turbine

VG-HAWT

- **Variable geometry via deformable trailing edge**
  - Effect variable pitch on small HAWTs
    - Control C_P as a function of wind
  - In-situ performance optimization and vibration reduction
    - Reduce fatigue and extend life
  - Low-footprint
    - Low cost and lightweight

- **Deformable trailing edge**
  - Distributed active "tabs"
  - Electrical power only
    - Shape memory alloy (SMA) actuator
  - Power required only to change shape NOT to maintain shape
  - Effectively zero form-factor
    - Retrofittable concept (can be applied to current blade designs)

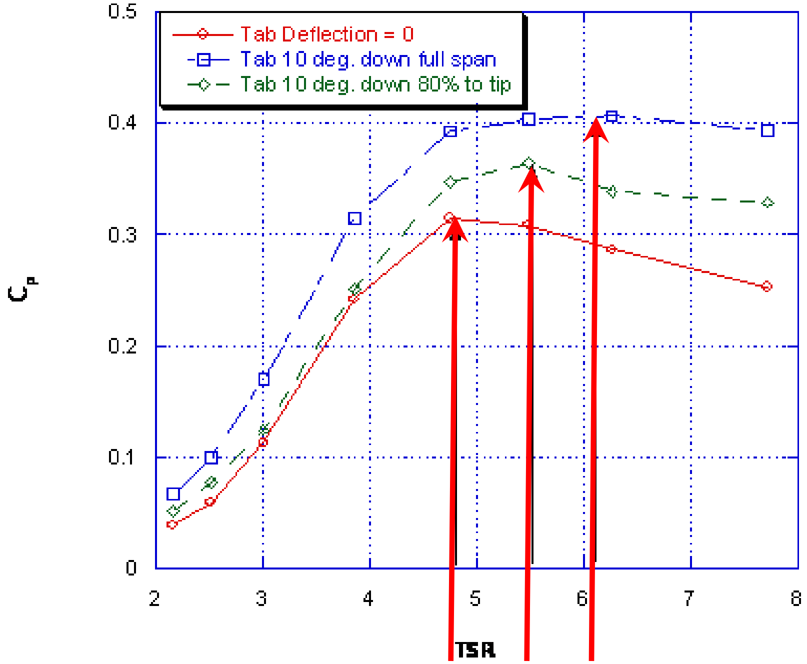


Powered tabs on a rotor blade

Tabs on a HAWT blade

VG-HAWT (cont'd)

- **Numerical analysis**
  - CDI's CHARM comprehensive analysis
    - Tabs modeled as flaps
    - Modified isolated UAE rotor
- **Predicted isolated turbine performance with tabs installed**
  - Reshape of the C_P curve
    - Increase in C_P
    - Broaden the peak of the C_P curve
  - Move C_P peak to different wind speeds
    - Effectively functions as variable pitch control for fixed pitch turbines
    - Effectively functions as variable RPM control for fixed speed turbines

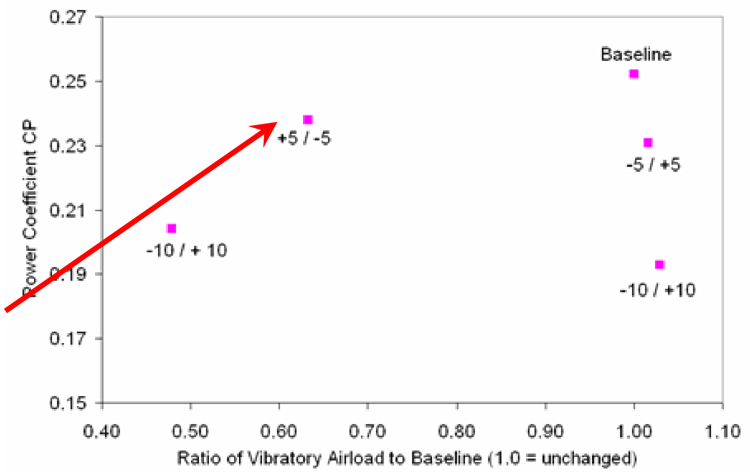


Peak of C_P moved to different tip speed ratios

VG-HAWT (cont'd)

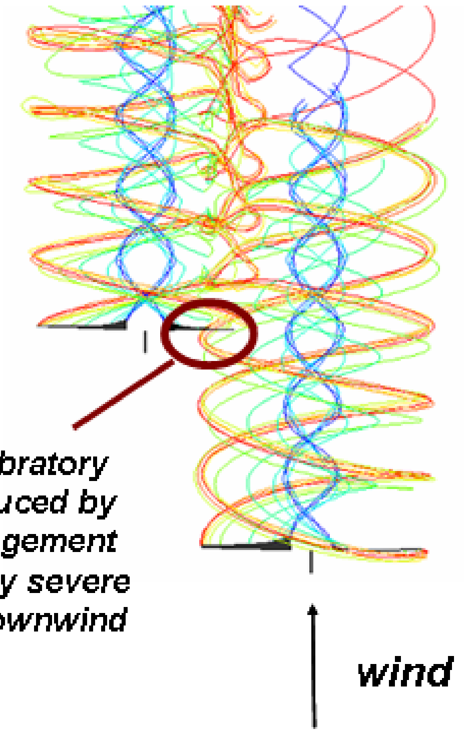
- **Numerical analysis**
  - CDI's CHARM comprehensive analysis
    - Tabs modeled as flaps
    - Modified isolated UAE rotor
- **Predicted performance of a downstream turbine with tabs installed from 50% span outboard**
  - Significant drop in vibratory loads for only modest power penalty

~35% reduction in vibratory loads for ~5% C_P reduction



Note freely interacting wakes.....

Examine vibratory loads produced by wake impingement (deliberately severe case) on downwind turbine

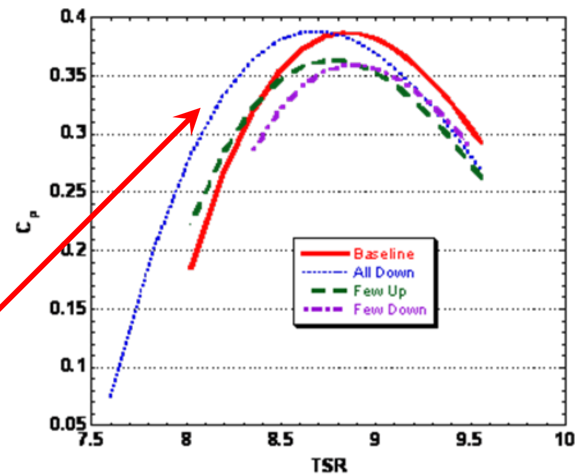


Wake prediction schematic for turbine-turbine interaction

VG-HAWT (cont'd)

- **HAWT test configuration**
  - Bergey XL1
  - Trailer mounted
  - Power dissipated with an Acme Electric Corp. PSSL-1000 1 kW programmable solid-state load

- **Summary of results**
  - Recovered Bergey published performance for tabs in neutral position (i.e. no C_P detriment)
  - Confirmed that tabs can move the peak of C_P curve



Peak of C_P moved to different TSRs

Bergey XL1 test rig with tabs installed

Continuum Dynamics, Inc.

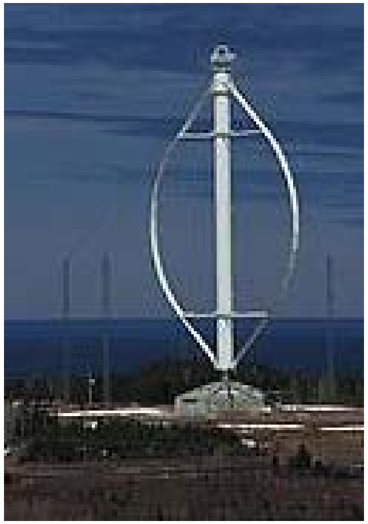
Variable Geometry
Vertical Axis Wind Turbine

VG-VAWT

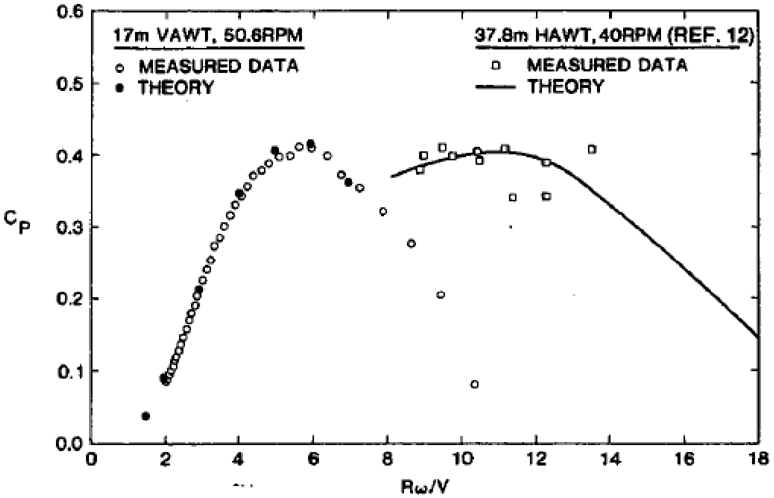
- **Significant work in the 1970-90s demonstrated the advantages of lift-based VAWTS**
  - C_P comparable to HAWTs
  - No yawing mechanism
  - Generator located at ground level

- **But**
  - Peak of C_P curve is narrower than HAWT
  - Low cost, reliable braking required to mitigate storm loads

- **Simplicity makes VAWT appealing for offshore applications, but how do you address these limitations in a cost effective manner?**
  - Variable geometry



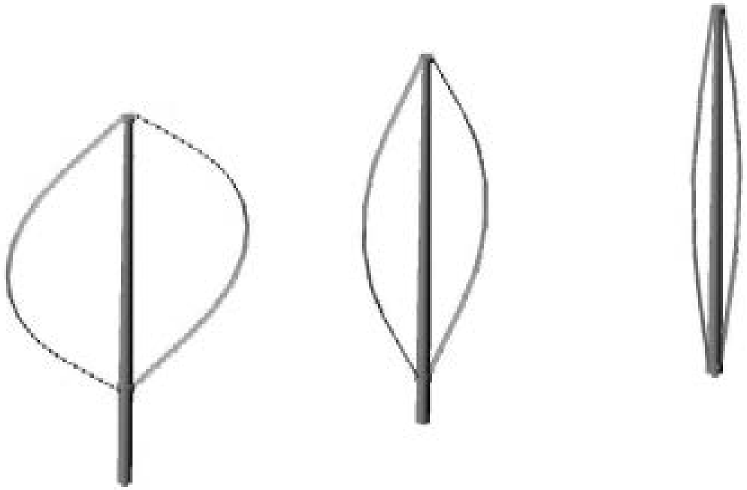
64m Eole VAWT (3.6 MW design)



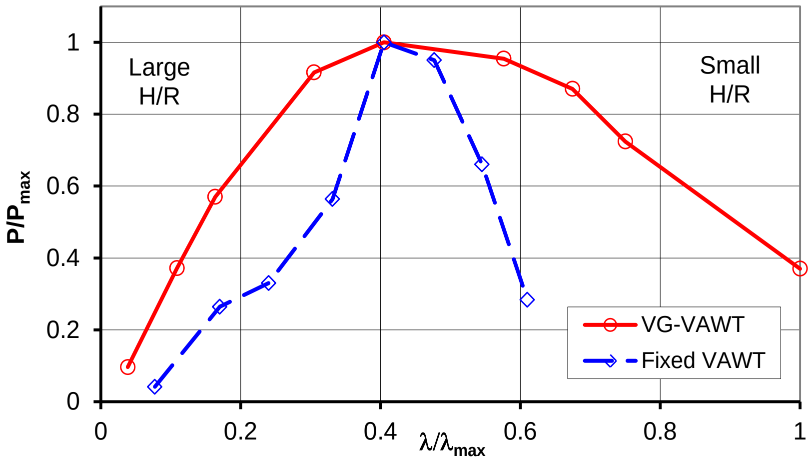
Measured and predicted HAWT and VAWT performance

VG-VAWT (cont'd)

- **Variable Geometry VAWT overview**
  - Change the capture area
    - Broaden the peak of the C_P curve
  - Furl the turbine blades onto the tower
    - Reduce storm loads
- **Blades:**
  - Hinged at the tower
    - Fold onto the tower for stowing and protection from storm loads
    - Fold away from the tower for increased power generation in low winds
  - Tapered thin blades
    - Large displacement and small strain
- **Shape change**
  - Top could move
    - Gravity assist for lower winds
    - Lower CG
  - Bottom could move
  - Gravity assist for stowing in high winds



Schematic of VG-VAWT

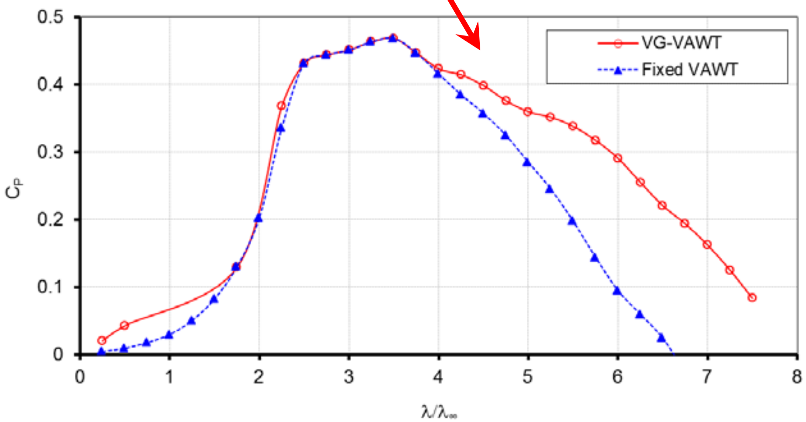


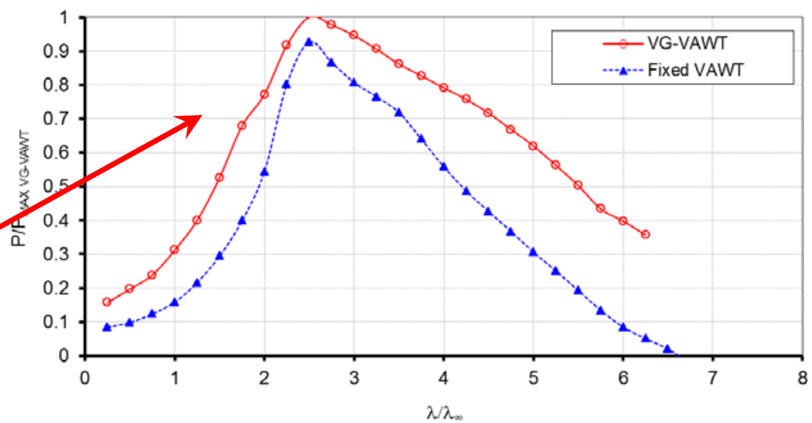
Sample VG-VAWT power curve

VG-VAWT (cont'd)

- **Numerical analysis**
  - Modified version of SANDIA DART code
  - Maximize power output for a given wind speed subject to blade stress limits
- **Predicted performance**
  - 23% increase in annual power generation when applied to actual location
    - Off the NJ coast
  - 50% COE reduction for offshore deployment
    - 50% reduction in capital cost
    - 25% reduction in O&M
    - 25% increase in power generation

Expanded C_P peak



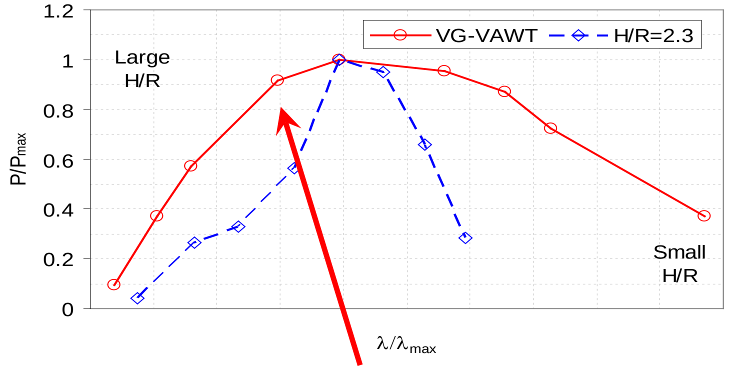


Increased power

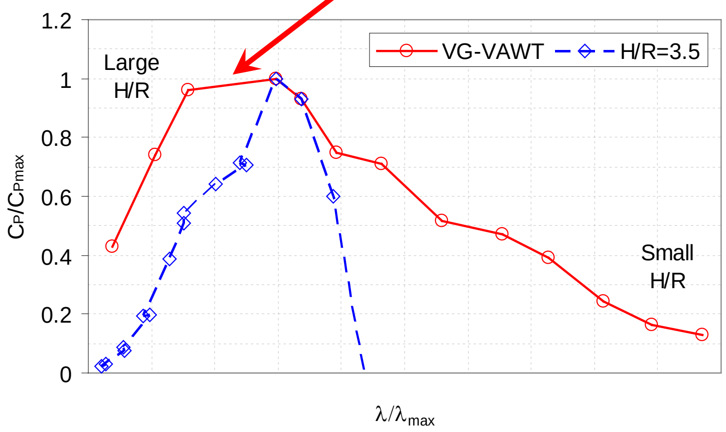
Predicted full-scale VG-VAWT power curves

VG-VAWT (cont'd)

- **Proof-of-concept wind tunnel model**
  - Flexible blades
  - Spring steel hinge connected to shaft
  - Upper and lower bearings used to change height
- **Wind tunnel test**
  - CDI 1ft x 1ft low turbulence tunnel
  - Measured power from shaft
- **Confirmed concept viability**



Expanded peak operating range



Wind tunnel model at various h/R

Measured VG-VAWT performance

VG-VAWT (cont'd)

- **Additional design considerations**
  - Furling mechanism design
  - Control system design
  - Aero-structural design
  - Variable geometry dynamics/stability
  - Fabrication
- **Furling mechanism**
  - Rack and pinion gear system with collars/bearings
  - Simplified swash-plate arrangement with hinges connecting the blade root to a collar
  - Shaft mounted jack-screws that winch the blade attachment point up and down as the tower rotates
- **Control system**
  - Direct model-based approach to capture non-linear aero-structural effects
  - Modal frequency avoidance
- **Blade fabrication**
  - Conventional lay-up
  - Pultrusion
  - Combination
- **Materials**
  - Decouple spar and skin requirements
  - Spar must be able to survive furling-induced fatigue
  - Skin can be relatively flexible

Conclusions

Conclusions

- **Variable geometry can reduce significantly COE by**
  - Optimizing power generation
  - Reducing vibratory blade/hub/generator loads (i.e. fatigue)
  - Minimizing storm loads
- **However, variable geometry must be implemented in a low cost reliable way**
  - Unconventional actuators can be a lightweight, small form factor approach
  - Reducing system complexity can help (VG-VAWT)
- **Two completely different approaches to implementing variable geometry have been presented**
  - SMA-based deformable trailing edge for a VG-HAWT
  - Flexible blade to effect a VG-VAWT
- **Proof-of-concept analysis and experiments demonstrated**
  - Ability of these approaches to broaden the C_P curve
  - Move the peak of the C_P curve to a difference wind speed
  - Reduce vibratory loads