Computational Strategies for Aero-mechanical Analysis in the Presence of Uncertainties

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NREL Workshop
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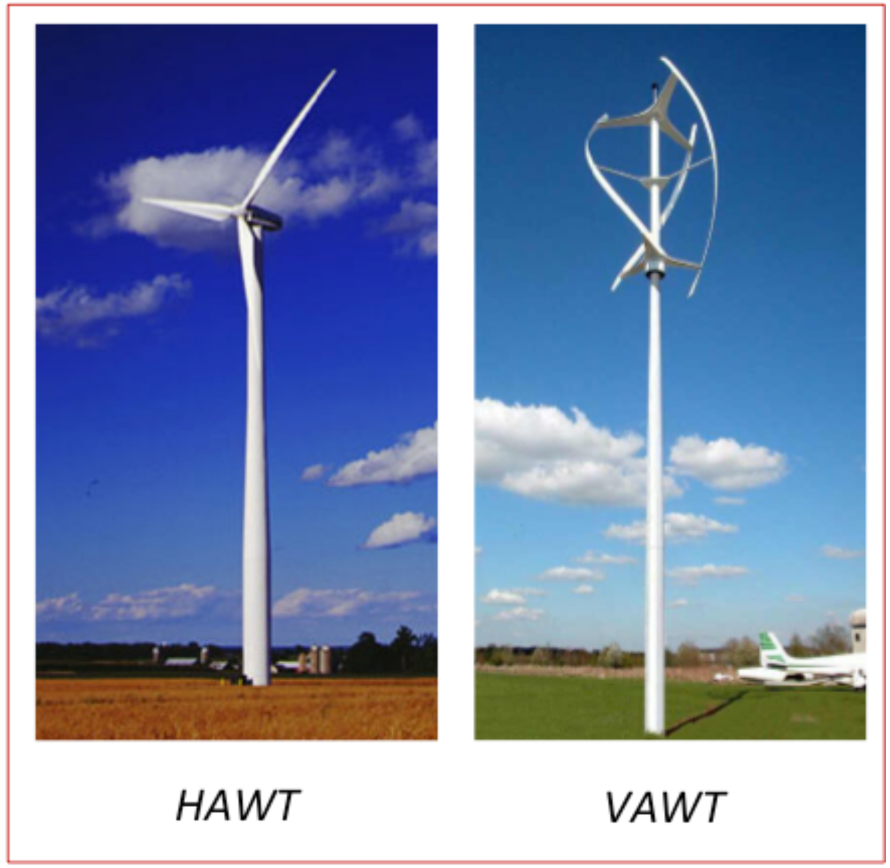
Objectives of the Project

- Develop, employ and critically compare novel methodologies for UQ in wind turbine applications
- Distinguish and estimate the importance of numerical errors, aleatory and epistemic uncertainties
- Establish approaches for multi-fidelity and gradient-enhanced UQ simulations
- Disseminate advanced UQ technologies to wind energy community



Wind Turbine Simulations

Energy extraction and environmental impact (noise) are critically linked to the aero-structural performance of turbine blades

Blade design is a truly multidisciplinary problem, requiring trade-offs between fluid dynamics, structural mechanics, acoustics, etc.

Uncertainties can play a significant role in the actual performance of the system and therefore it is important to

- explicitly acknowledge their presence
- quantify their effects

Under DOE/ASCR funding we are developing uncertainty quantification algorithms to analyze (and optimize) wind turbines under uncertainty

Uncertainties & Errors

Numerical discretization errors result from numerical solution procedures, e.g. grid resolution, time-stepping, etc.

Natural variability – randomness – is intuitively connected to wind scenarios, manufacturing tolerance, dust/insect contamination, etc.

Modeling errors are associated to assumptions present in physical model we use to represent reality, e.g. turbulence models, laminar/turbulence transition prediction, stall, etc.

Objectives of This Talk

Provide background on the simulation techniques and examples of uncertainty scenarios considered in the project

Briefly introduce

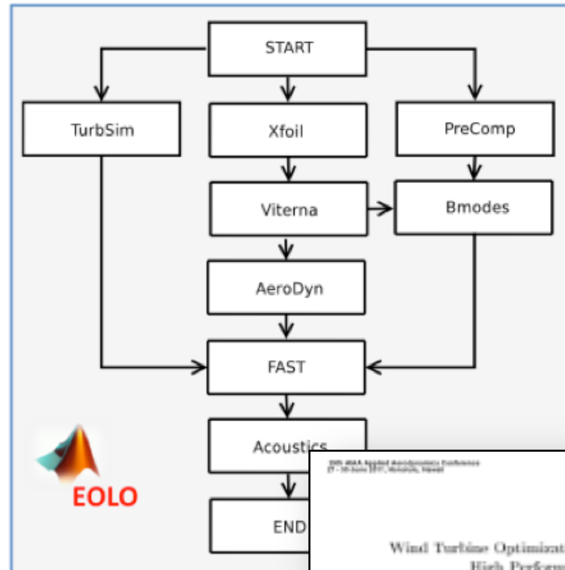
- Low-Fidelity Tools: Eolo (FAST) & Cactus
- High-Fidelity Tools: SU OverTurns, ASC Sierra Thermal/Fluids

UQ Techniques will be described in the following talk

Low-Fidelity Tools

HAWT - EOLO

- Assembled the EOLO framework based on NREL tools (e.g. FAST)
- Includes aerodynamics, structural dynamics, turbulent wind flows, noise
- The aerodynamic analysis are based on xfoil (low-fidelity flow prediction tool) rather than experimental correlation
- Blade stall and transition behavior are characterized using semi-empirical models (Viterna and e^N, respectively)
- EOLO is driven by matlab and interfaced with Dakota and accommodate UQ Analysis and Robust Design




AIAA 2011-3806

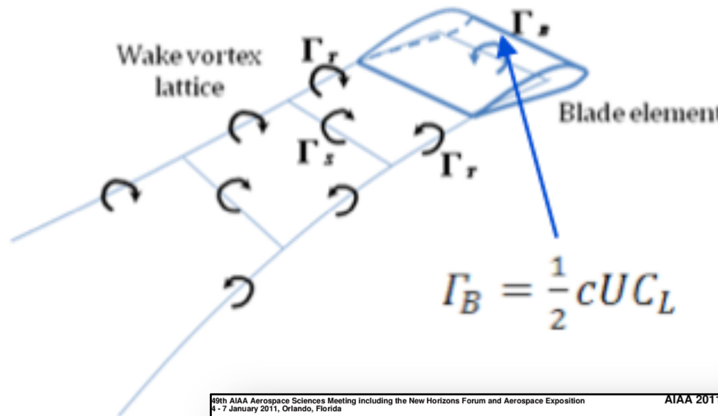
Wind Turbine Optimization Under Uncertainty with High Performance Computing

I. Introduction and motivations

AIAA-2011-3806

VAWT - CACTUS

- CACTUS: Code for Axial and Cross-Flow Turbine Simulations
- Rigid-body aerodynamic model for single horizontal- or vertical-axis wind turbine rotor design
- Wake modeled with free vortex method
- Gormont and Leishmann-Beddoes dynamic stall models
- Free surface potential flow model for marine turbines
- Recently added ability to simulate IEC gust cases, allows for UQ analysis of extreme loads
- Cactus is Interfaced with Dakota



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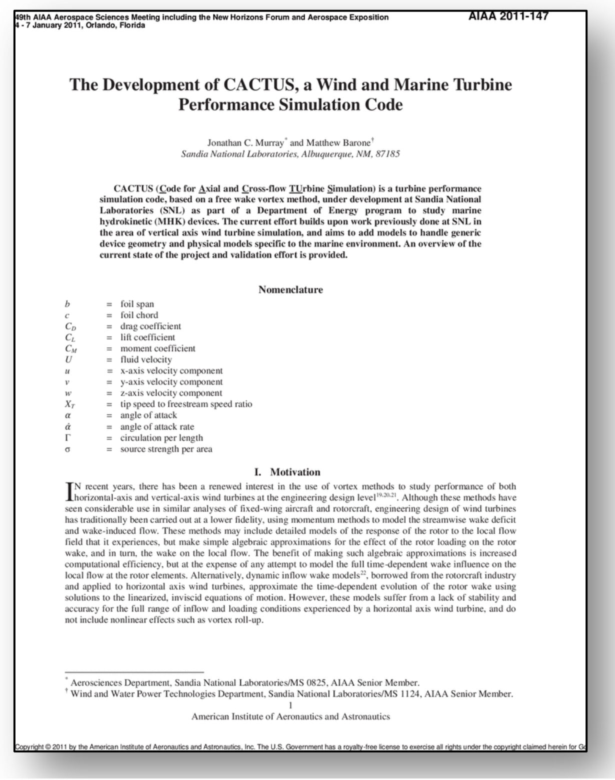

49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition
4 - 7 January 2011, Orlando, Florida
AIAA 2011-147

The Development of CACTUS, a Wind and Marine Turbine Performance Simulation Code

Jonathan C. Murray* and Matthew Barone†
Sandia National Laboratories, Albuquerque, NM, 87185

CACTUS (Code for Axial and Cross-flow TUrbine Simulation) is a turbine performance simulation code, based on a free wake vortex method, under development at Sandia National Laboratories (SNL) as part of a Department of Energy program to study marine hydrokinetic (MHK) devices. The current effort builds upon work previously done at SNL in the area of vertical axis wind turbine simulation, and aims to add models to handle generic device geometry and physical models specific to the marine environment. An overview of the current state of the project and validation effort is provided.

Nomenclature

b = foil span
c = foil chord
C_D = drag coefficient
C_L = lift coefficient
C_M = moment coefficient
U = fluid velocity
u = x-axis velocity component
v = y-axis velocity component
w = z-axis velocity component
X_T = tip speed to freestream speed ratio
α = angle of attack
$\dot{\alpha}$ = angle of attack rate
Γ = circulation per length
σ = source strength per area

I. Motivation

IN recent years, there has been a renewed interest in the use of vortex methods to study performance of both horizontal-axis and vertical-axis wind turbines at the engineering design level[19,20,21]. Although these methods have seen considerable use in similar analyses of fixed-wing aircraft and rotorcraft, engineering design of wind turbines has traditionally been carried out at a lower fidelity, using momentum methods to model the streamwise wake deficit and wake-induced flow. These methods may include detailed models of the response of the rotor to the local flow field that it experiences, but make simple algebraic approximations for the effect of the rotor loading on the rotor wake, and in turn, the wake on the local flow. The benefit of making such algebraic approximations is increased computational efficiency, but at the expense of any attempt to model the full time-dependent wake influence on the local flow at the rotor elements. Alternatively, dynamic inflow wake models[22], borrowed from the rotorcraft industry and applied to horizontal axis wind turbines, approximate the time-dependent evolution of the rotor wake using solutions to the linearized, inviscid equations of motion. However, these models suffer from a lack of stability and accuracy for the full range of inflow and loading conditions experienced by a horizontal axis wind turbine, and do not include nonlinear effects such as vortex roll-up.

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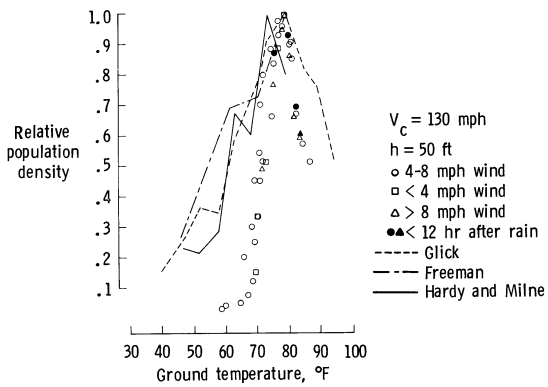
Uncertainty Scenarios

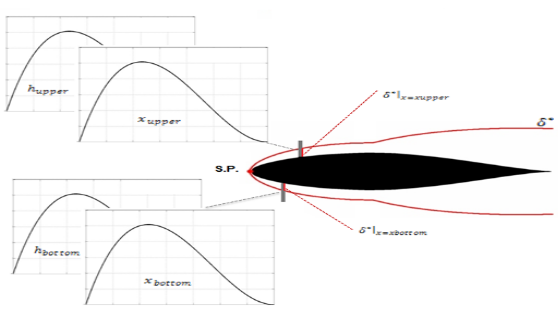
Analysis Under Uncertainty - Aleatory

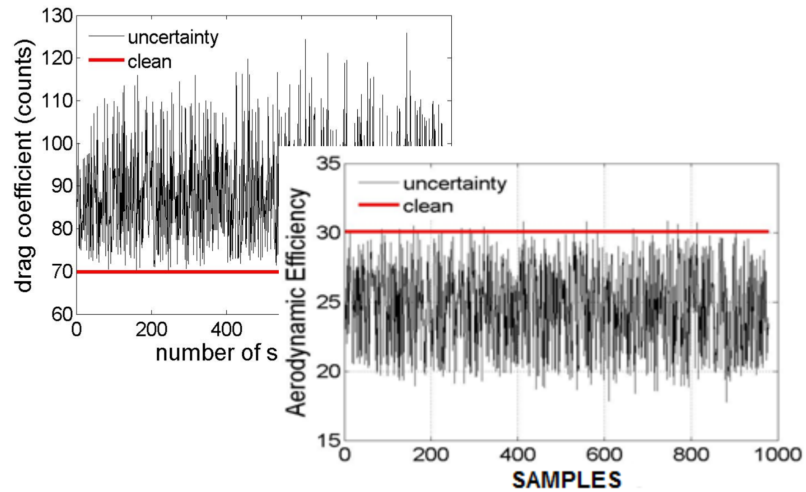
1) Collect information:

Insect contamination

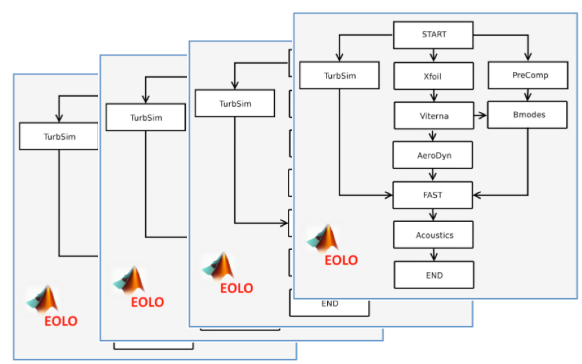


2) Construct a probabilistic model of the uncertainties (4 r.v.s)





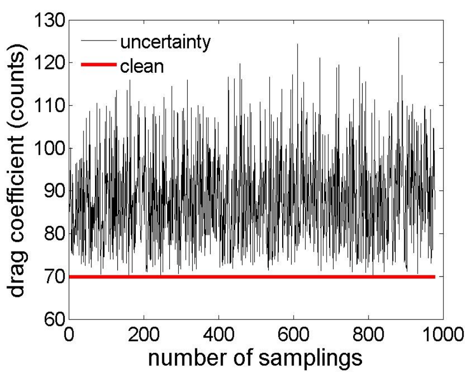
4) Compute statistics of the Quantities of interest



3) Perform UQ propagation

Analysis Under Uncertainty - Aleatory

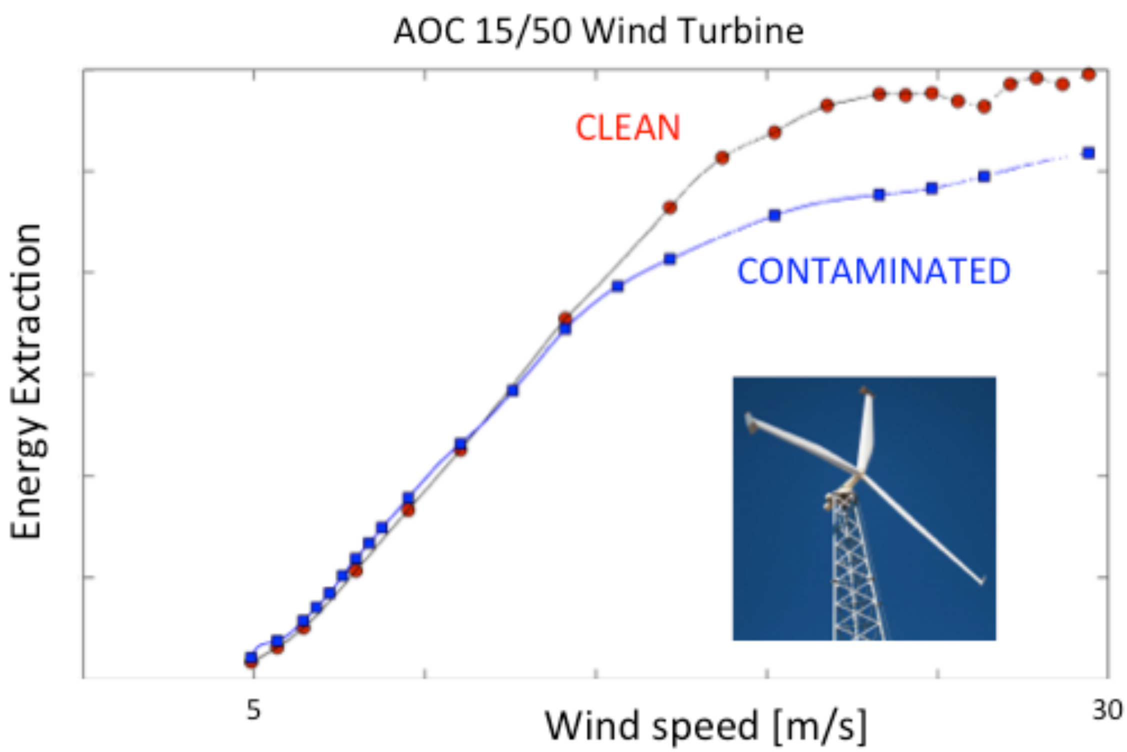
Analysis under uncertainty: effect of insect contamination of overall power extraction



Expected Energy Extraction

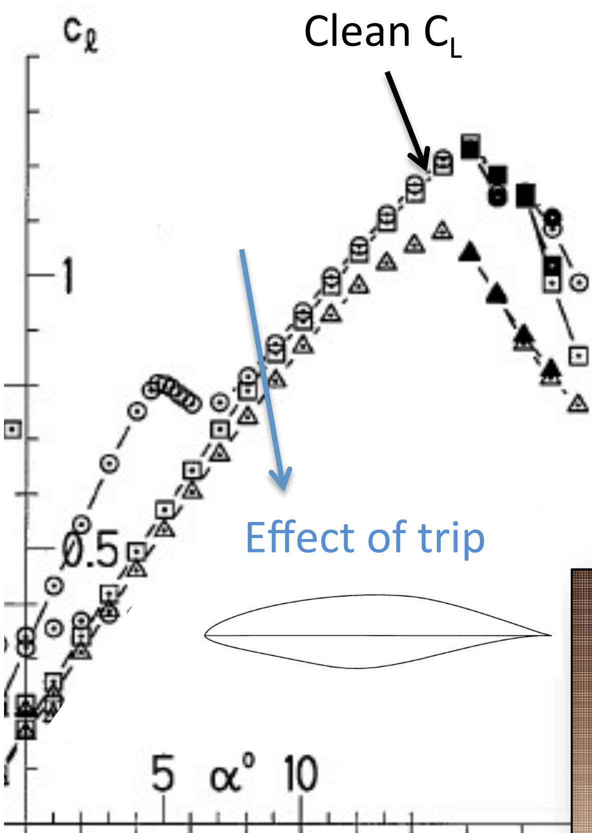
$$\int_{\Omega} E(\vec{\xi})p(\vec{\xi})d\vec{\xi}$$

Ω is a 4D space (spanned by the uncertain variables)



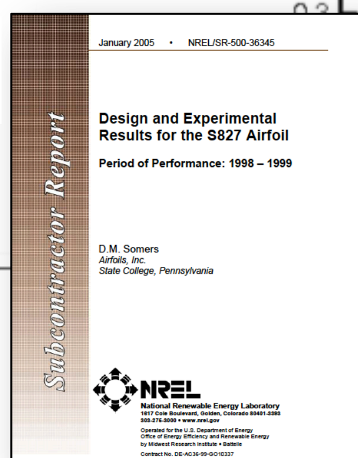
>>> but can we really predict transition?

Physical Modeling



NREL S827 Airfoil

NREL/SR 500 36345



January 2005 • NREL/SR-500-36345

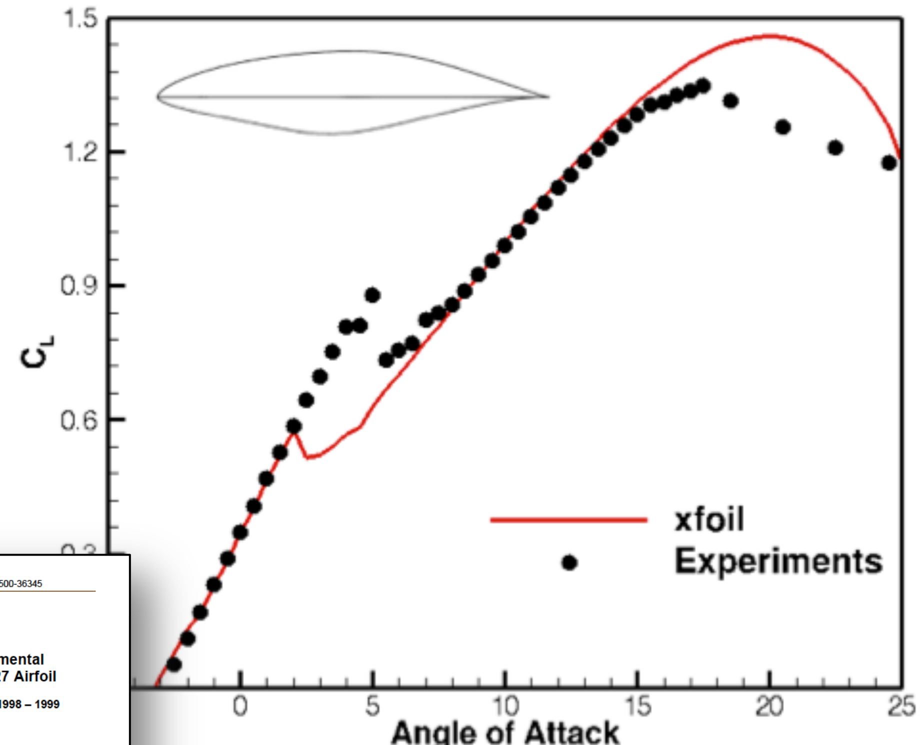
Subcontractor Report

Design and Experimental Results for the S827 Airfoil

Period of Performance: 1998 – 1999

D.M. Somers
Airfoils, Inc.
State College, Pennsylvania

NREL
National Renewable Energy Laboratory



Computational Study with Xfoil

Physical Modeling

- The e^N method in Xfoil is simple and effective but limited in scope
- RANS models promise to provide more detailed information regarding viscous effects: γ-Re_c transition model developed by Menter et al.

$$\frac{\partial \rho\gamma}{\partial t} + \frac{\partial \rho u_i \gamma}{\partial x_i} = P_\gamma - E_\gamma + \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_f}\right)\frac{\partial \gamma}{\partial x_i}\right],$$

Intermittency
(γ=0/1 > laminar/turbulent)

$$\frac{\partial \rho \widetilde{Re}_{\theta t}}{\partial t} + \frac{\partial \rho u_i \widetilde{Re}_{\theta t}}{\partial x_i} = P_{\theta t} + \frac{\partial}{\partial x_i}\left[\sigma_{\theta t}(\mu + \mu_t)\frac{\partial \widetilde{Re}_{\theta t}}{\partial x_i}\right]$$

Critical Re number

Empirical Correlations

Elsner et al. 2008

$$Re_{\theta c} = F_p \widetilde{Re}_{\theta t}$$
$$\widetilde{Re}_{\theta t\,max} < 250:$$
$$F_{length} = 0.5$$
$$\widetilde{Re}_{\theta t\,max} \geq 250:$$
$$F_{length} = 0.274 + 0.0039\,\widetilde{Re}_{\theta t\,max} - 2.13\cdot 10^{-5}\,\widetilde{Re}_{\theta t\,max}^{\;2} + 3.65\cdot 10^{-8}\,\widetilde{Re}_{\theta t\,max}^{\;3}$$

Sorensen 2009

$$Re_{\theta c\_Sorensen} = \beta\left(\frac{\widetilde{Re}_{\theta t} + 12000}{25}\right) + (1-\beta)\left(\frac{7\cdot\widetilde{Re}_{\theta t} + 100}{10}\right)$$
$$\beta = \tanh\left[\left(\frac{\widetilde{Re}_{\theta t} - 100}{400}\right)^4\right]$$
$$F_{length\_Sorensen} = \min\left[150\cdot\exp\left[-\left(\frac{\widetilde{Re}_{\theta t}}{120}\right)^{1.2}\right] + 0.1;\quad 30\right]$$

Malan et al., 2009

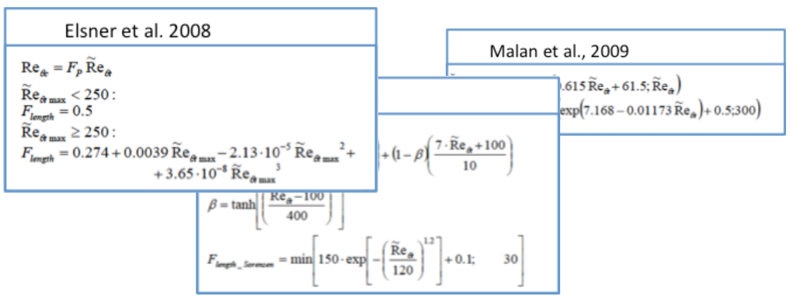
$$Re_{\theta c\_Malan} = \min\left(0.615\,\widetilde{Re}_{\theta t} + 61.5;\, \widetilde{Re}_{\theta t}\right)$$
$$F_{length\_Malan} = \min\left(\exp\left(7.168 - 0.01173\,\widetilde{Re}_{\theta t}\right) + 0.5;300\right)$$

Which one?

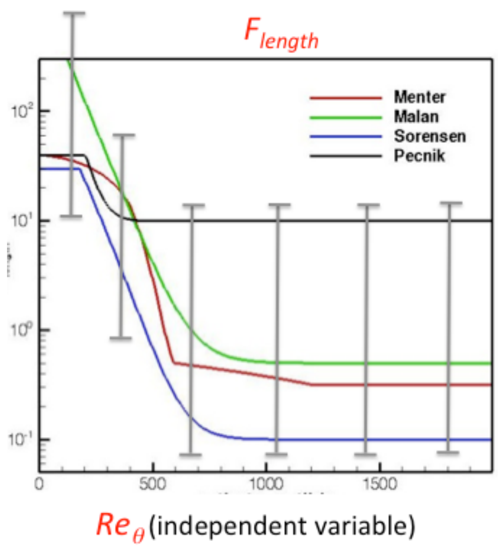
Analysis Under Uncertainty - Epistemic

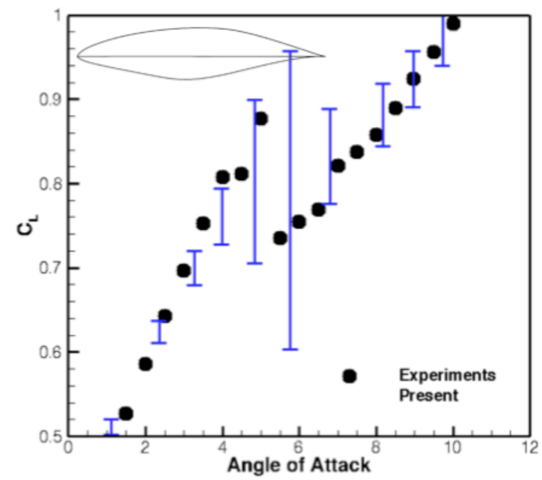
1) Collect information:

Expert Opinions

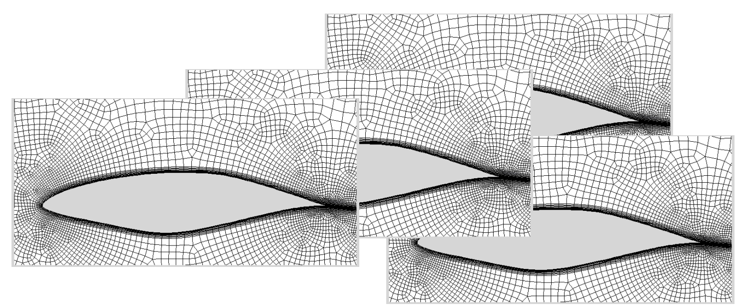


2) Construct a representation of the model uncertainties





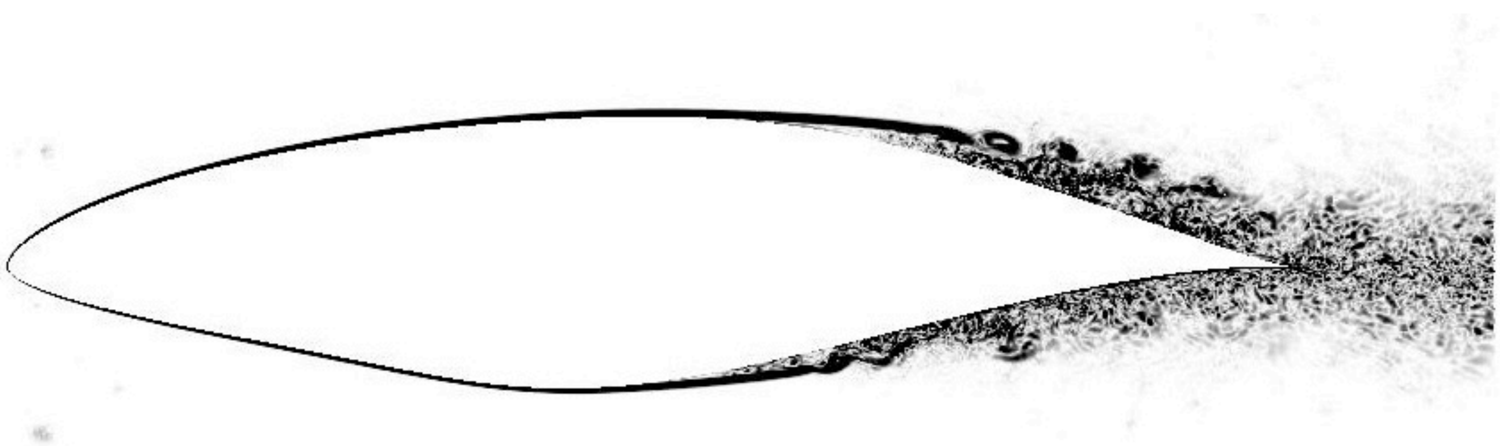
4) Compute intervals on the Quantities of interest



3) Perform UQ propagation

High Fidelity?

- Xfoil and γ-Re models do require extensive calibration
- Exponential increase in computational resources holds the promise of using first-principle models
- High-fidelity modeling – Large Eddy Simulations



High-Fidelity Tools

Barriers to High-Fidelity Modeling

Wind turbines are inherently multi-physics systems

- Need to be high-fidelity across disciplines
- Aeroloads are the first target here

Computational methods

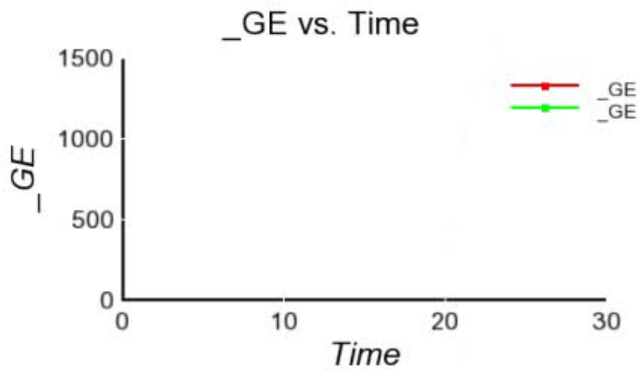
- Impact of numerical discretization error has to be assessed
- Handle moving/sliding geometries
- Massively parallel and scalable implementation

Uncertainty Quantification

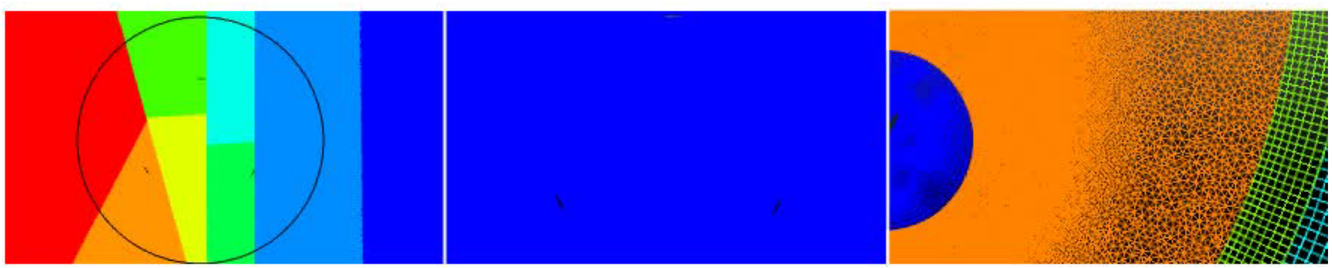
- It might be challenging to describe uncertainty sources (e.g. inflow turbulence, gusts)
- Modeling assumptions still present

Scalability for High-Fidelity Simulations

- Sliding mesh algorithm requires efficient parallel search and dynamic modification of linear systems



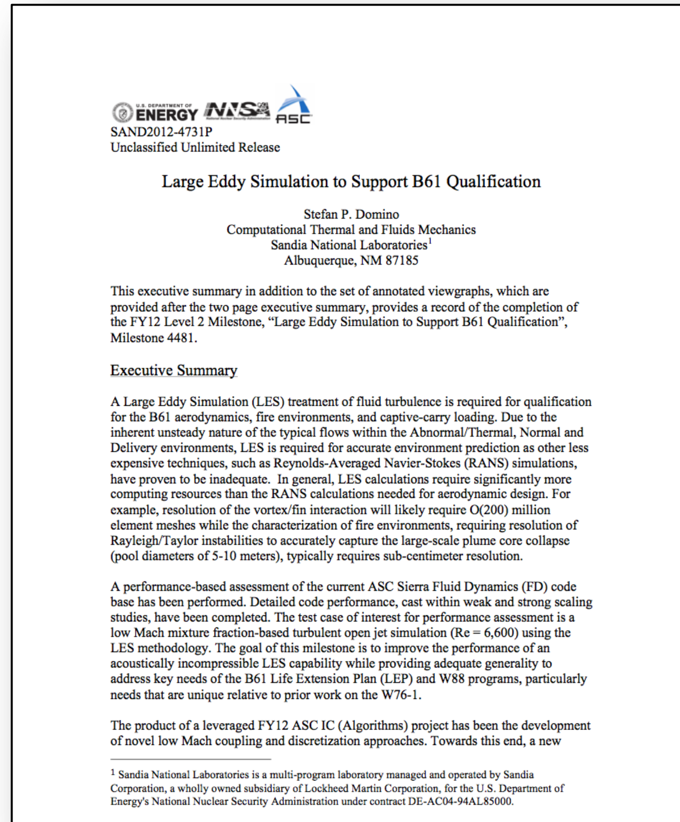
Turbulent Kinetic Energy



Parallel Decomposition Turbulent Viscosity Mesh Interface

Leverage from Previous Efforts

- Stanford CTR code base
- Sandia's Sierra code base
- Each provide:
  - Massively parallel computing
  - High quality numerics on unstructured grids with code verification suite in place
  - Demonstrated code scalability
    - ***LES to support B61 Qualification***, SAND2012-4731P
    - Scaling demonstrated on unstructured hex meshes of 1.2 billion on > 65,000



SAND2012-4731P
Unclassified Unlimited Release

Large Eddy Simulation to Support B61 Qualification

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Computational Thermal and Fluids Mechanics
Sandia National Laboratories[1]
Albuquerque, NM 87185

This executive summary in addition to the set of annotated viewgraphs, which are provided after the two page executive summary, provides a record of the completion of the FY12 Level 2 Milestone, "Large Eddy Simulation to Support B61 Qualification", Milestone 4481.

Executive Summary

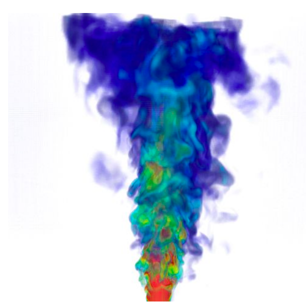
A Large Eddy Simulation (LES) treatment of fluid turbulence is required for qualification for the B61 aerodynamics, fire environments, and captive-carry loading. Due to the inherent unsteady nature of the typical flows within the Abnormal/Thermal, Normal and Delivery environments, LES is required for accurate environment prediction as other less expensive techniques, such as Reynolds-Averaged Navier-Stokes (RANS) simulations, have proven to be inadequate. In general, LES calculations require significantly more computing resources than the RANS calculations needed for aerodynamic design. For example, resolution of the vortex/fin interaction will likely require O(200) million element meshes while the characterization of fire environments, requiring resolution of Rayleigh/Taylor instabilities to accurately capture the large-scale plume core collapse (pool diameters of 5-10 meters), typically requires sub-centimeter resolution.

A performance-based assessment of the current ASC Sierra Fluid Dynamics (FD) code base has been performed. Detailed code performance, cast within weak and strong scaling studies, have been completed. The test case of interest for performance assessment is a low Mach mixture fraction-based turbulent open jet simulation (Re = 6,600) using the LES methodology. The goal of this milestone is to improve the performance of an acoustically incompressible LES capability while providing adequate generality to address key needs of the B61 Life Extension Plan (LEP) and W88 programs, particularly needs that are unique relative to prior work on the W76-1.

The product of a leveraged FY12 ASC IC (Algorithms) project has been the development of novel low Mach coupling and discretization approaches. Towards this end, a new

[1] Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

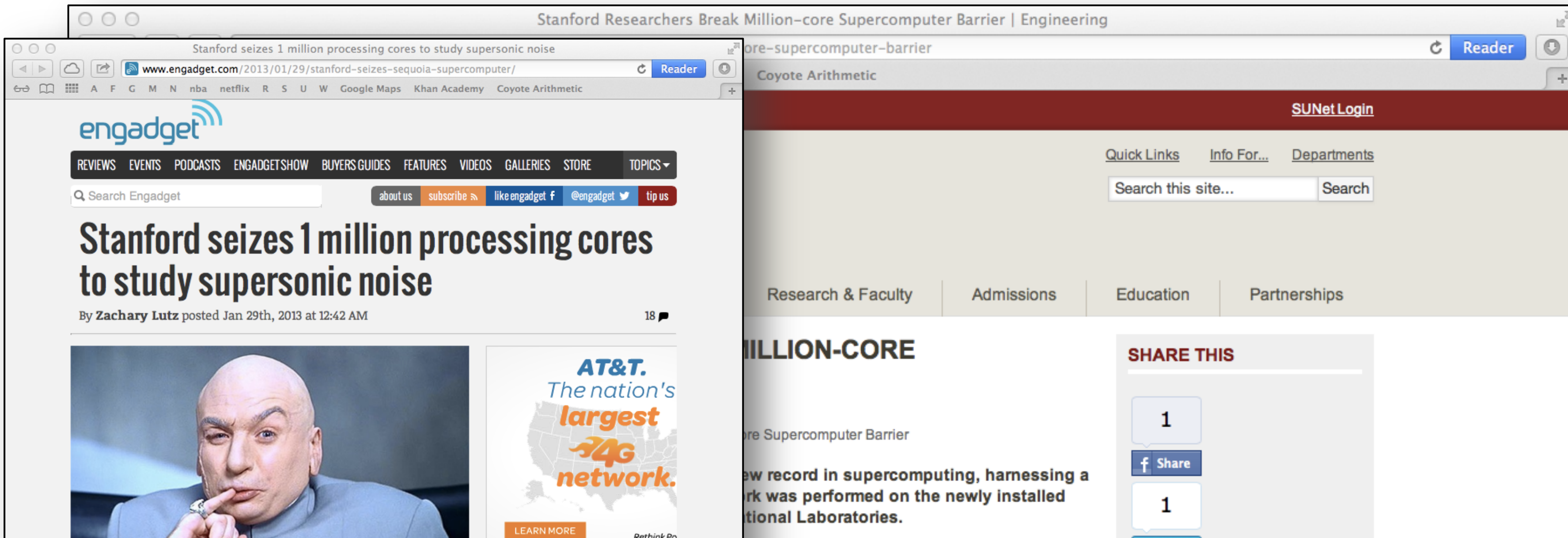
400 million dof object in fire



Turbulent jet (1.2 billion)

ADVANCED SIMULATION & COMPUTING™

Extreme Scalability



LLNL Sequoia BG/Q: 1.5M cores,
#2 Supercomputer in the world

VAWT/HAWT - OverTurns

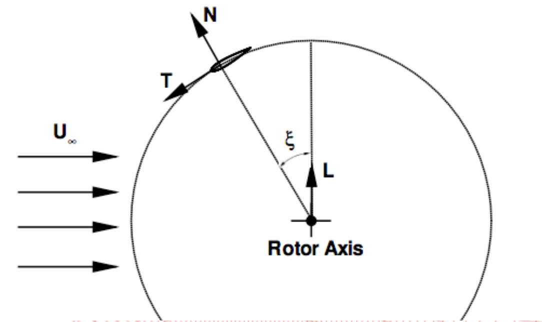
- Compressible, vertex-based RANS Solvers with 3rd-5th order discretization
- Overset meshes for moving & deforming components
- System of discrete equations solved using second order backwards differencing scheme (time-marching) or globally spectral (time-spectral)
- Physical Models:
    - Turbulence models: K-omega, Spalart Allmaras, v2-f, v2-f/ASBM
    - Transition models: Langtry-Menter γ-Re_t
- Full Discrete Adjoint (in space-time domain)
    - Used to calculate gradients
    - Error estimation (space, time, stochastics)

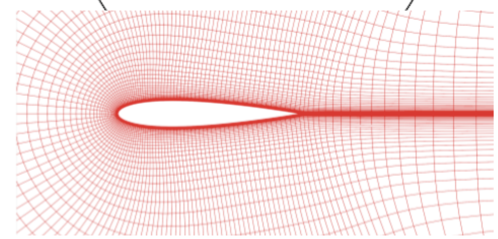
VAWT/HAWT – Sierra Thermal/Fluids

- Low Mach (variable density, acoustically incompressible) vertex-based (CVFEM and EBVC) generalized unstructured solvers developed for turbulent reacting flow
  - Hex, tet, pyr, wedge, quad, tri
- Advanced sliding mesh capabilities including both Discontinuous Galerkin and "halo" approaches (extrusion of mesh)
- Fully implicit, second order time integration with low dissipation advection operators
- Physical Models:
  - Turbulence models: RANS (K-omega, SST, etc.) and LES (Dynamic Smagorinsky, Ksgs, etc)
- Built upon the demonstrated massively parallel Sierra code base along with multi-physcis coupling including FSI

VAWT – OverTurns

- One-bladed vertical axis wind turbine setup [Oler and Strickland, 1983]
- NACA0015 airfoil, c/R=0.25, TSR=7.5



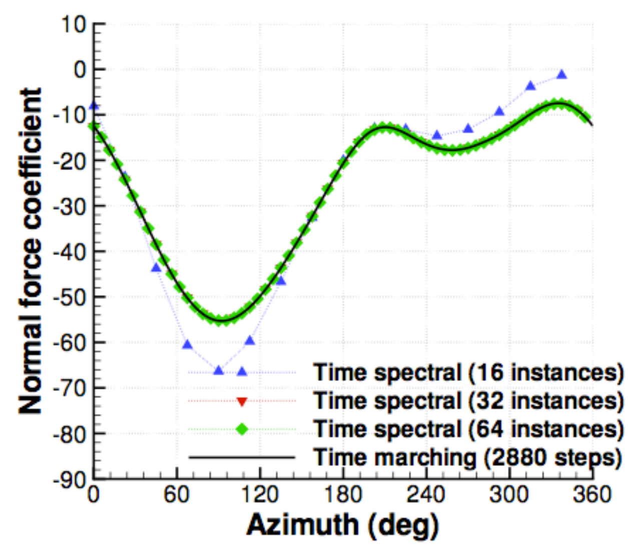


Time Marching

$$\frac{\partial u}{\partial t} + R(u) = 0$$

Time Spectral

$$\begin{cases} \dfrac{\partial u^n}{\partial t'} + D_t u^n + R(u^n) = 0 \\[2em] D_t u^n = \displaystyle\sum_{m=-\frac{N}{2}+1}^{k=\frac{N}{2}-1} d_m u^{m+n} \end{cases}$$



VAWT - Adjoints

- Sensitivity Analysis (Vertical force and Power Coefficient)

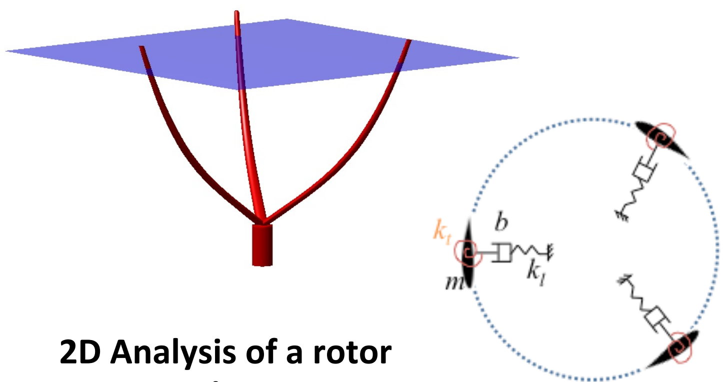
C_L	dC_L/dM_∞		C_P	dC_P/dM_∞	
	Adjoints	FD		Adjoints	FD
1.5089	22.9478	22.9478	3.3170	216.5934	216.5934

- Error Estimation (Power Coefficient)

Domain	f	$f+\epsilon_{cc}$	$\epsilon_{cc}/\epsilon_{relative}$
V. Coarse ($57 \times 17 \times \{8\}$)	-6.4309	2.8003	1.12
Coarse ($113 \times 33 \times \{16\}$)	1.8197	4.2433	1.56
Baseline ($225 \times 65 \times \{32\}$)	3.3170	3.6583	1.25
Fine ($449 \times 129 \times \{64\}$)	3.5813	–	–

VAWT – Sierra

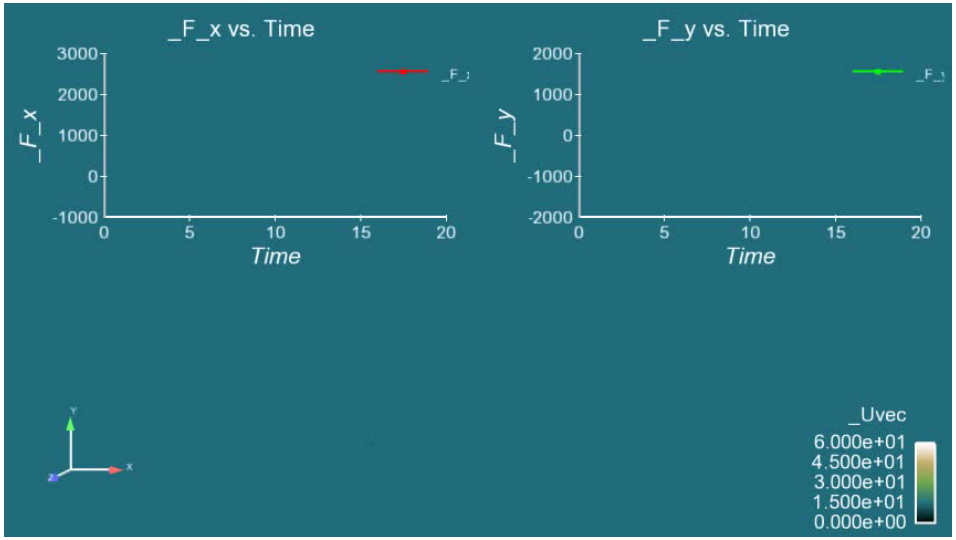
Notional 5 MW, 3-bladed "U-VAWT" Design



2D Analysis of a rotor cross-section

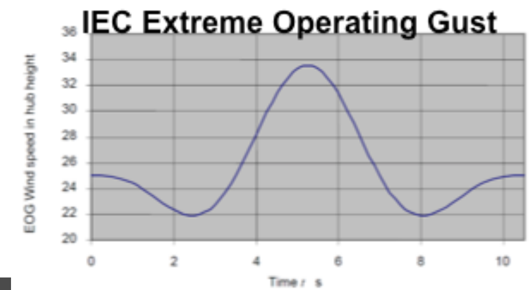
- A sample of the types of simulations that are being run
- In general, one full simulation (~1 million elements) requires ~one day of simulation time

Design Parameter	Value
Rotor Radius (m)	74
Height from base of rotor (m)	85
Number of Blades	3
Blade Chord (m)	1.52
Blade attachment point (fraction of chord)	0.5
Rotational Speed (RPM)	7.66
Airfoil	SNL 0018/50
Chord Reynolds number	5,400,000



VAWT – Wind Gusts

- The tools are also planned to be deployed to application spaces including wind gusts



Velocity magnitude shown; TI = 5%; Strickland, Smith and Sun (SAND81-7017)

Summary & Conclusions

- Accounting for Uncertainties is Important for Estimating Performance with Confidence

- We have built a computational framework that enables us to
  - Quantify uncertainty due to variability
  - Asses errors due to numerical discretization
  - Estimate uncertainties due to modeling assumptions:
  - Balance computational effort in accounting for all the sources of uncertainty and errors
  - Achieve extreme scalability on large-scale simulations

- The framework naturally spans multiple fidelity levels and enables analysis and design using large-scale HPC systems

How do we effectively quantify the uncertainty?
>>> Dakota >>> Mike Eldred

Acknowledgements

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Sandia National Laboratories

Dongbin Xiu

Purdue University

Thank You

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