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# Aeroelastic Simulation Of Wind Turbines Using Free Vortex Methods And Strategies For Accelerating The Computation

## A Doctoral Dissertation Proposal

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Department of Mechanical and Industrial Engineering

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# Acknowledgements


- Dissertation Committee
  - Dr. Matthew A. Lackner
  - Dr. James F. Manwell
  - Dr. Hans Johnston
- University of Massachusetts
  - Department of Mechanical Engineering
  - Wind Energy Center
- MGHPCC
- NREL

# Outline

- Background
  - Offshore Floating Wind Turbine
  - Aerodynamic Models
  - Free Vortex Method
  - WInDS
- Acceleration of WInDS
- Coupling WInDS with FAST/AeroDyn
  - Compiling on MGPHCC
  - Results
- Near-Term Goals
- Concluding Remarks

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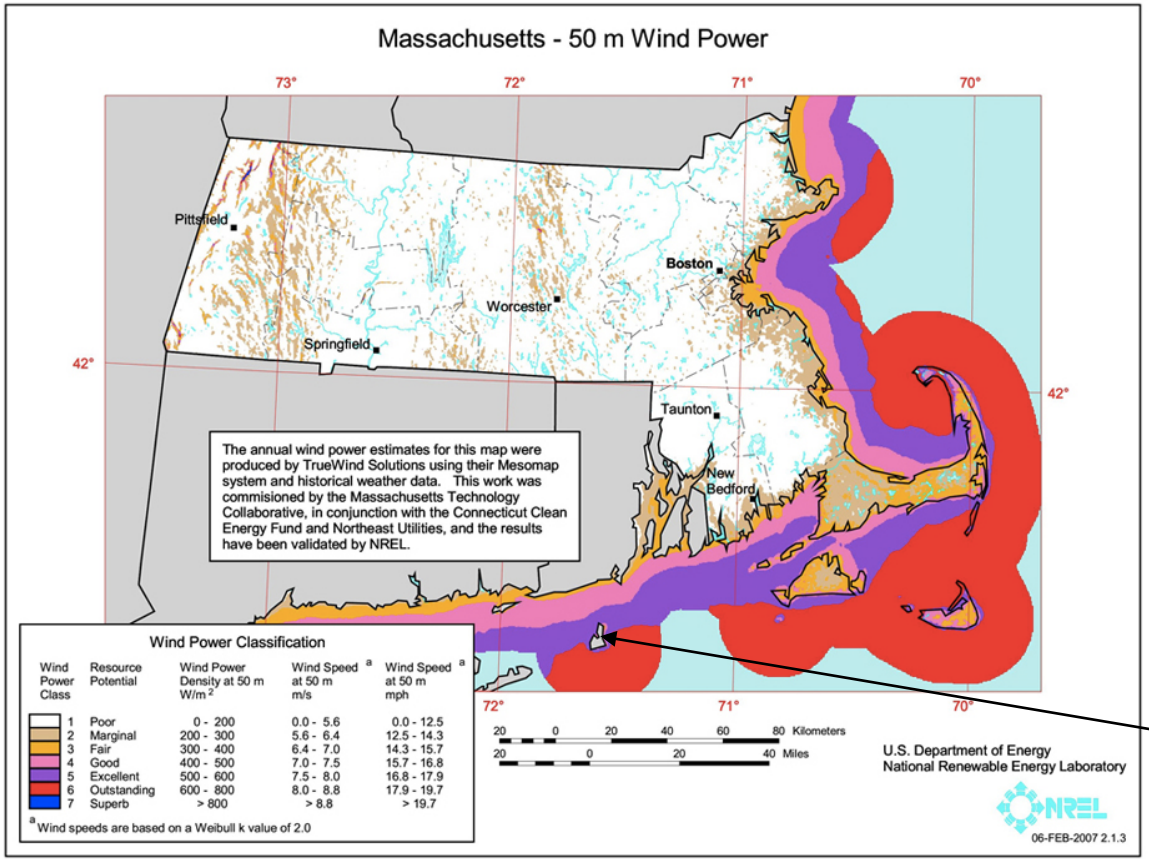
# Offshore vs. Onshore Wind




Block Island

Figure Credit: Department of Energy (2014)

# OFWT Concepts

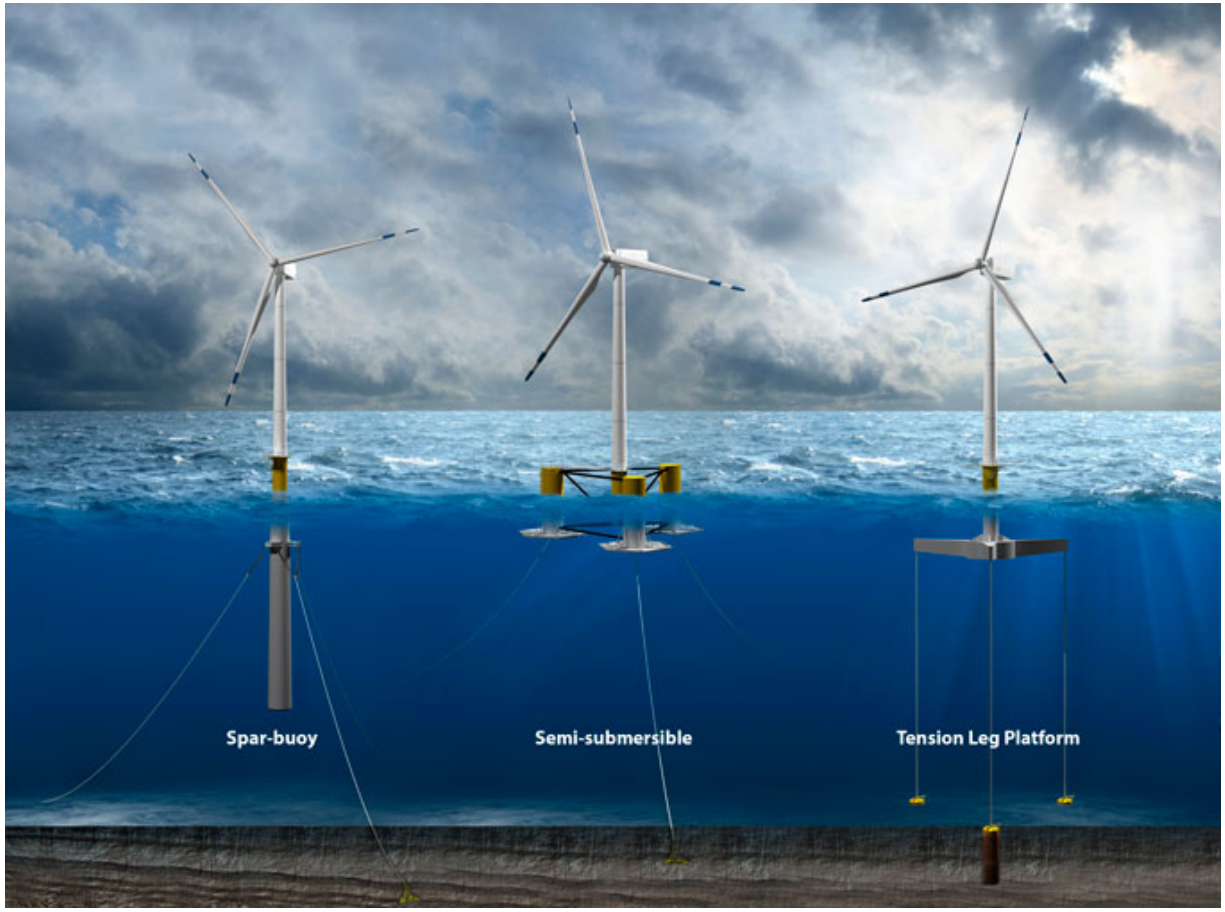
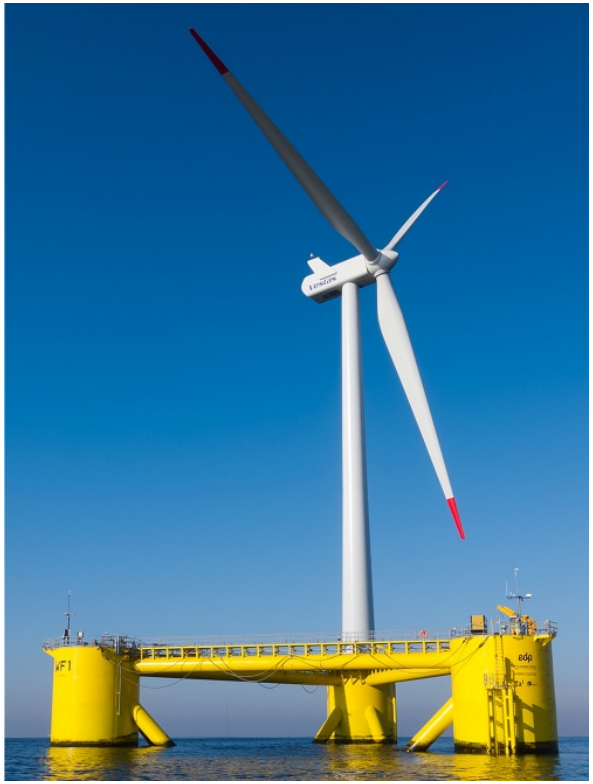



Figure Credit: Illustration by Joshua Bauer, NREL

# Full-scale OFWTs

(a) Hywind floating wind turbine

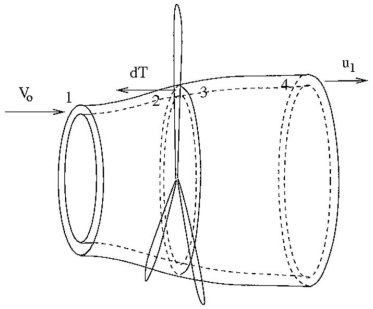


(b) WindFloat floating wind

(c) The Mistubishi 7MW floating turbine

# Aerodynamic Models

- Blade element momentum theory
- Computational fluid dynamics
- Potential flow methods
  - Prescribed vortex method
  - Free vortex method
  - Panel Method

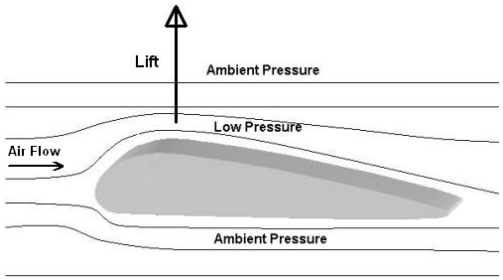


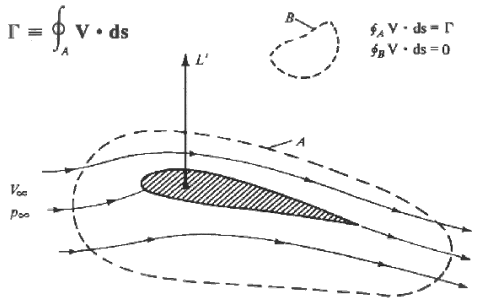

(a) BEM

(b) CFD

Figure Credit:
- http://fluidsengineering.asmedigitalcollection.asme.org/article.aspx?articleid=1439572
- http://www.windpowerengineering.com/construction/simulation/simulating-the-turbine-simulating-the-site

# Free Vortex Method (2D)




Iteration to get Cl

$$L = c\Delta P$$

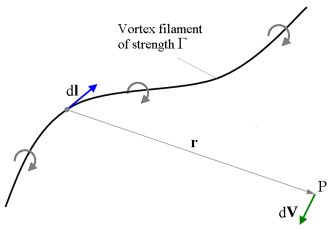
Kutta–Joukowski theorem

$$L' = \frac{1}{2}\rho_\infty U_\infty^2 C_l c dy = \rho_\infty U_\infty \Gamma$$

Calculate lifting force

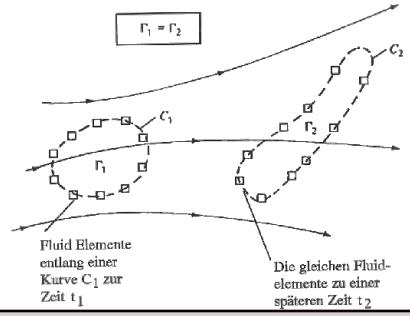
$U_\infty$ ← Biot-Savart Law

$$d\mathbf{U} = -\frac{\Gamma}{4\pi}\frac{\mathbf{r} \times d\mathbf{l}}{|\mathbf{r}|^3}$$



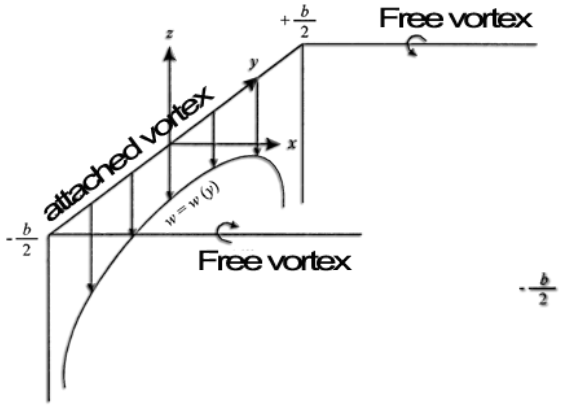

$\Gamma$ ← Kelvin's circulation theorem

$$\frac{D\Gamma}{Dt} = 0$$

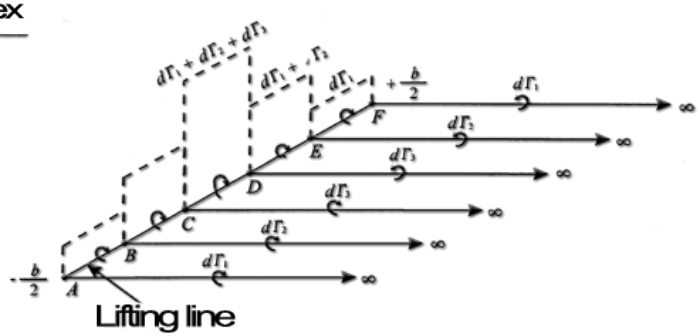


# Free Vortex Method (3D)

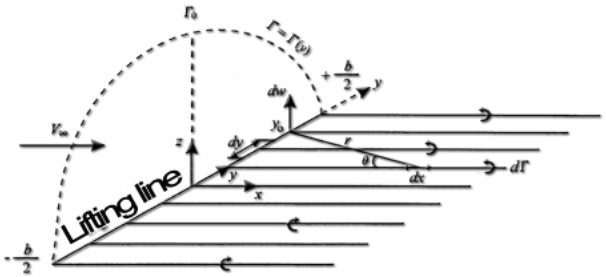
- Prandtl lifting-line theory




(a) Single vortex




(b) Superimposed vortices




(c) Infinite number of vortices

Figure Credit:
- http://ggrot323.weebly.com/waterfowl.html
- http://heli-air.net/2016/02/25/the-kutta-joukowski-theorem-and-the-generation-of-lift/
- https://en.wikipedia.org/wiki/Biot%E2%80%93Savart_law
- http://heli-air.net/2016/02/25/kelvin-s-circulation-theorem-and-the-starting-vortex/
- http://www.heliciel.com/en/helice/calcul-helice-aile/Theorie-%20ligne%20portante-Prandtl.htm

# Wake Induced Dynamics Simulator (WInDS)

- Written by Sebastian and Lackner at Umass-Amherst
- Lifting line theory (LLT) -based free vortex wake method (FVM)
- Modeling the offshore floating wind turbine(OFWT) aerodynamics to a higher degree of accuracy than is possible via momentum balance methods.
- WInDS natively incorporates the multiple DOFs present in offshore floating wind turbines

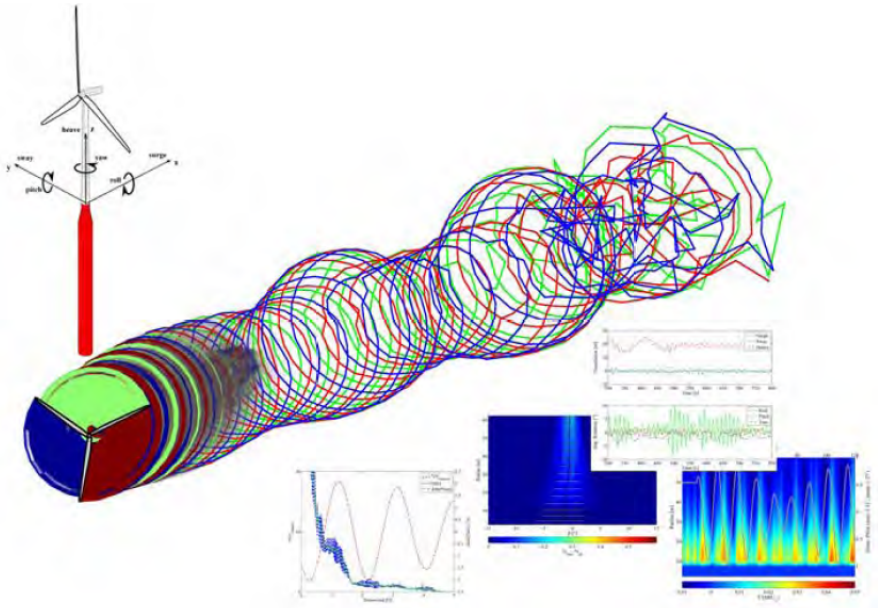


Figure Credit: Thomas Sebastian

# Pros and Cons of WInDS

- Pros:
  - Inherent aerodynamic flexibility as compared to BEM.
  - Second order accuracy.
  - Core modeling.
  - Ground effects by deVelder and dynamic stall by Gaertner.
- Cons
  - Structural positions and velocities are computed *a priori* and as such, cannot react to the aerodynamic loading or structural dynamics.
  - Written in MATLAB and the O($N^2$) calculation is very slow.

Focus of this dissertation

Reference: Nathaniel B. deVelder's thesis

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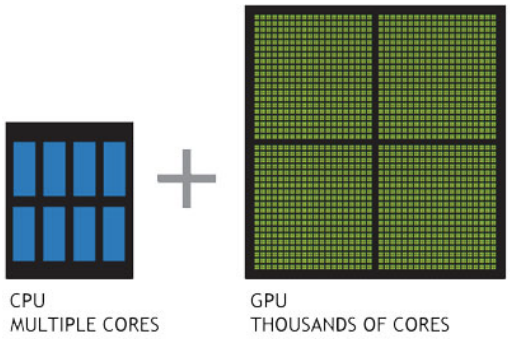
# Approaches to Biot-Savart Law

- Device: GPU vs CPU
- Algorithm: Treecode vs Fast Multipole Method



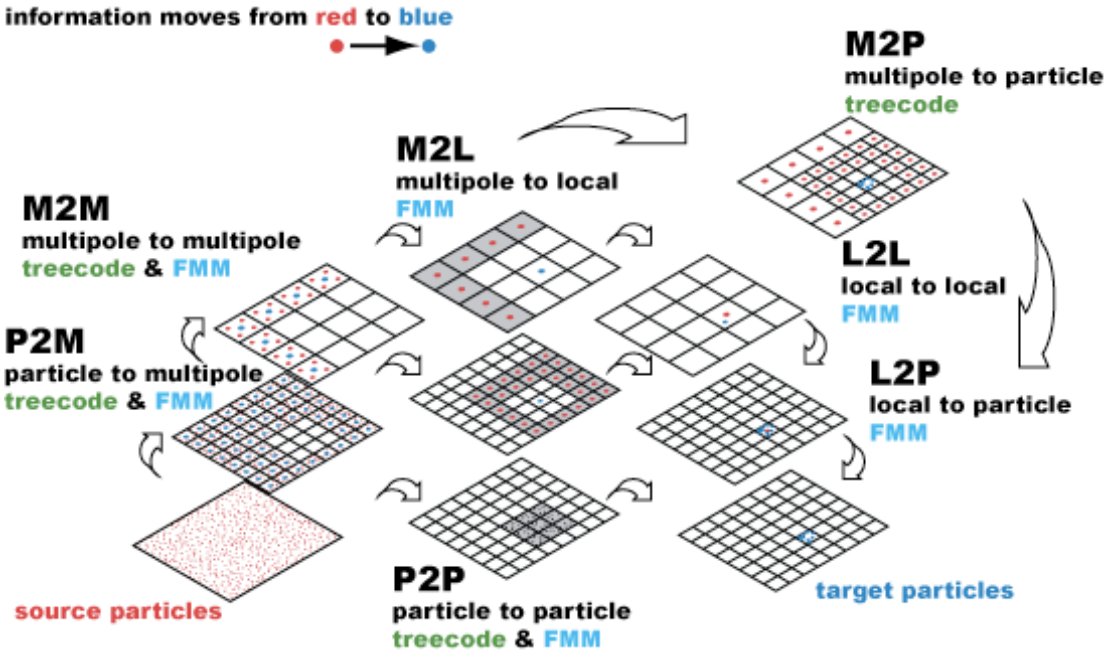
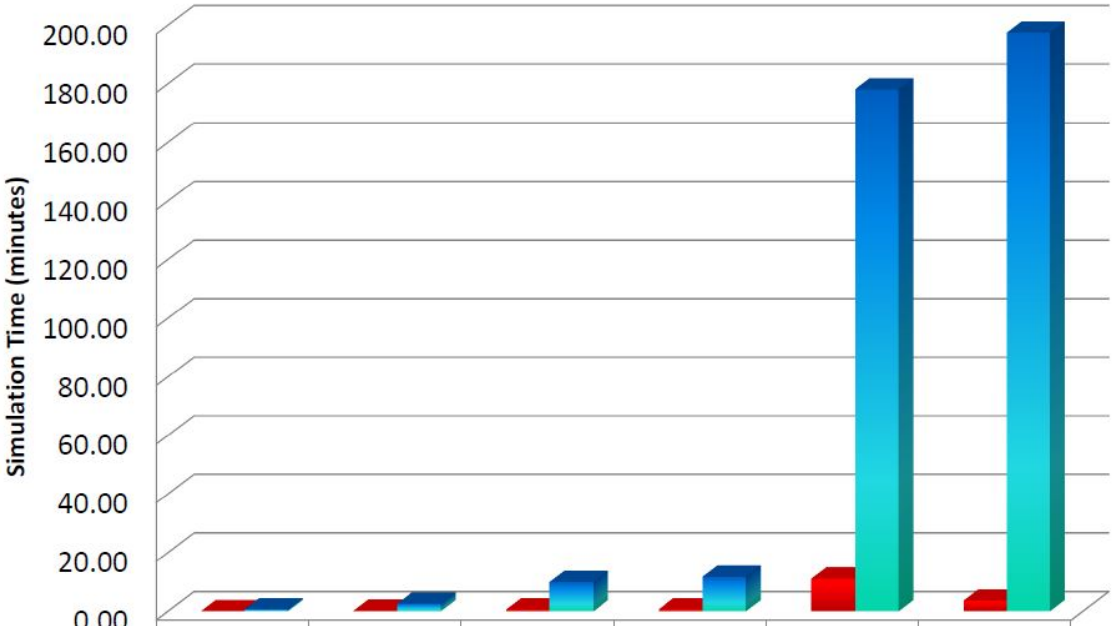




Figure Credit:
- http://www.bu.edu/exafmm
- http://www.nvidia.com/object/what-is-gpu-computing.html

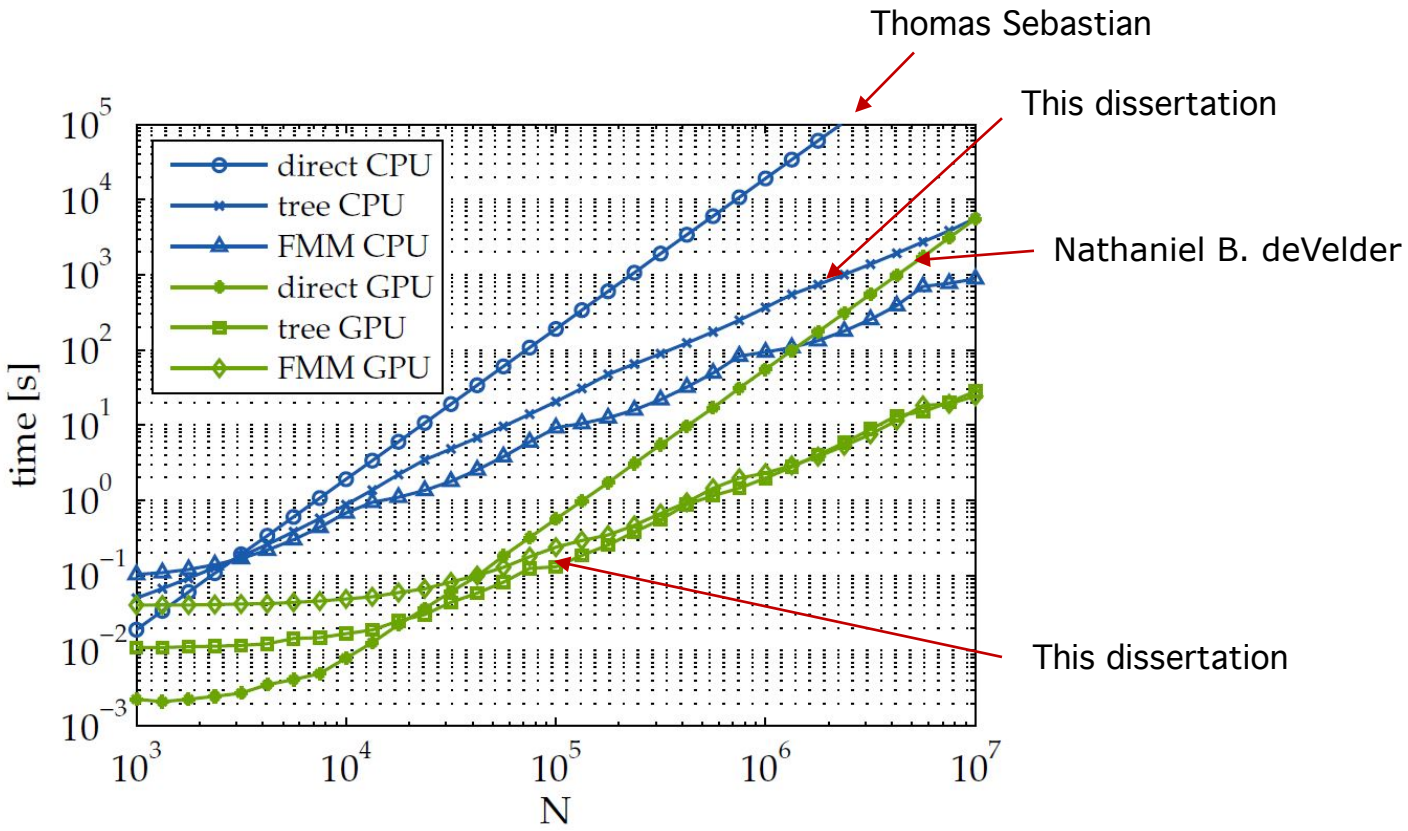
# Previous Research




| | NVIDIA Tesla K20c | NVIDIA GTX580 | NVIDIA GTS450 | OpenMP | C MEX Serial | MATLAB Only |
|---|---|---|---|---|---|---|
| N=48600 | 0.06 | 0.17 | 0.63 | 0.73 | 11.11 | 3.67 |
| N=194400 | 0.70 | 2.64 | 9.97 | 11.73 | 178.13 | 197.51 |

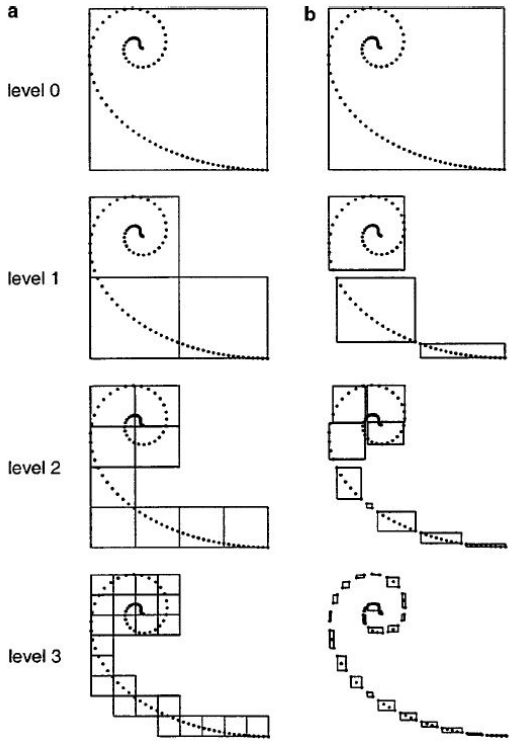
Results from Nathaniel B. deVelder's thesis

# Comparison of Performance




Comparison of algorithms. Yokota, R., & Barba, L. A. (2011)

# Treecode Algorithm



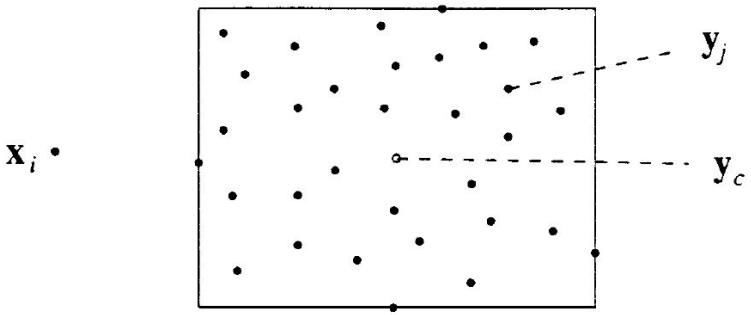
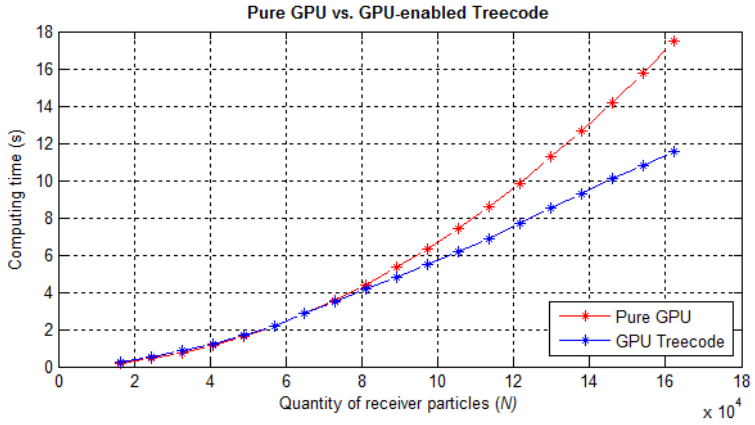
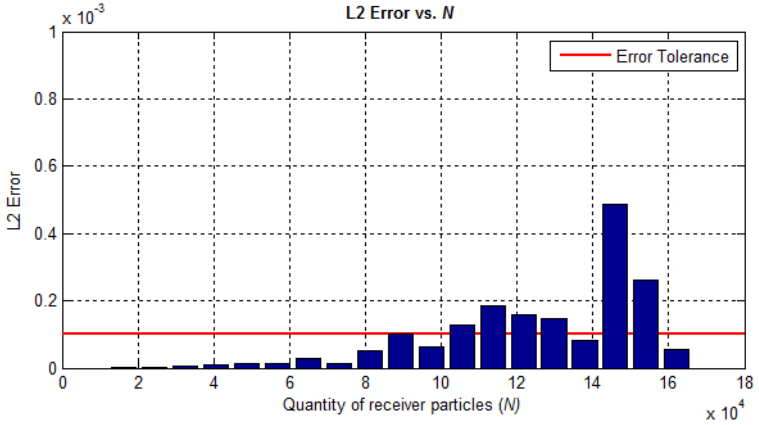




Figure: Treecode Algorithm
Lindsay, K., & Krasny, R. (2001)

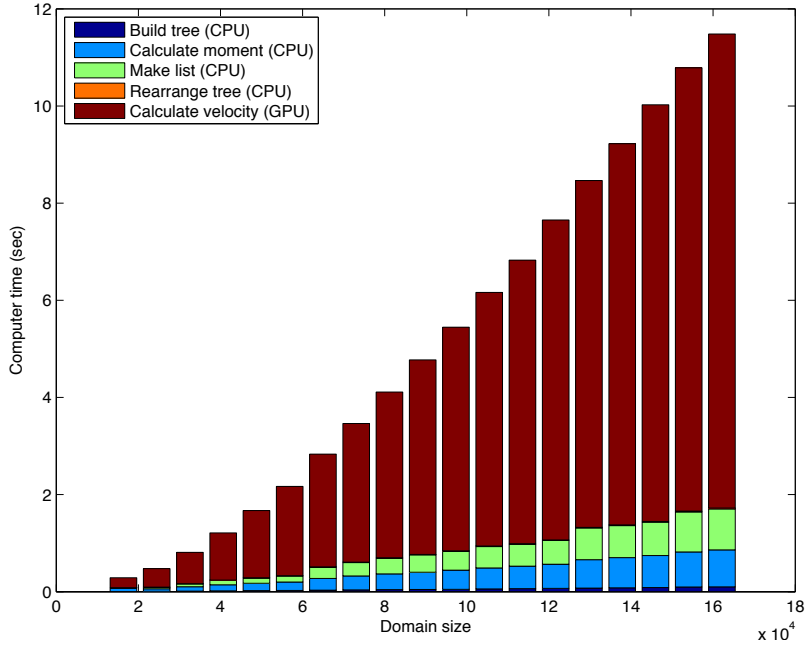
# Parallelized Treecode in CUDA




(a) Running time

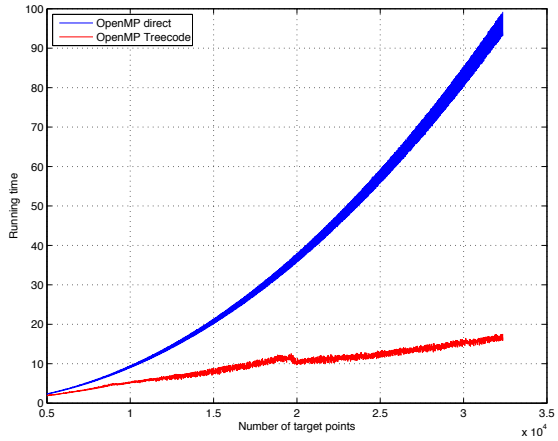



(b) Error

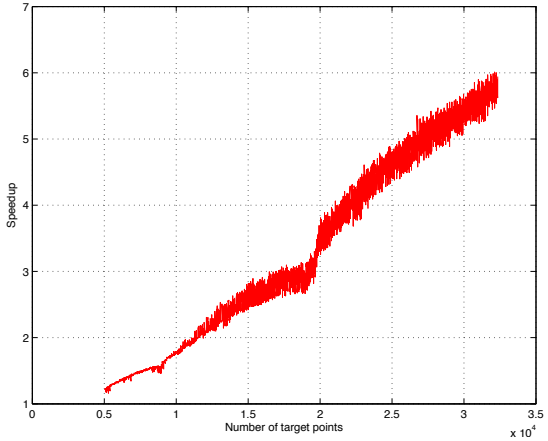



(c) Time of each part

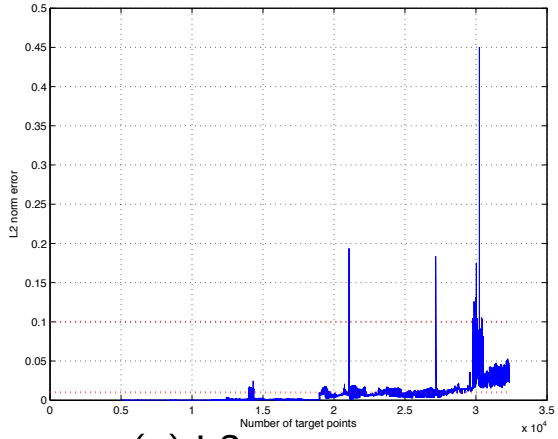
# Parallelized Treecode in Fortran



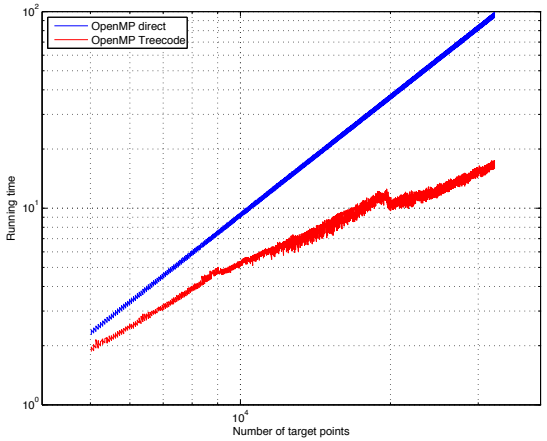

(a) Running time




(b) Speedup

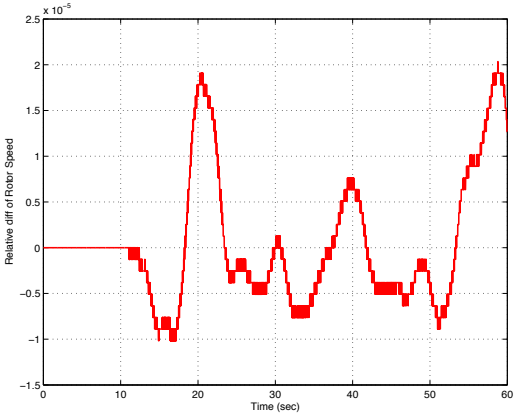



(c) L2 norm error

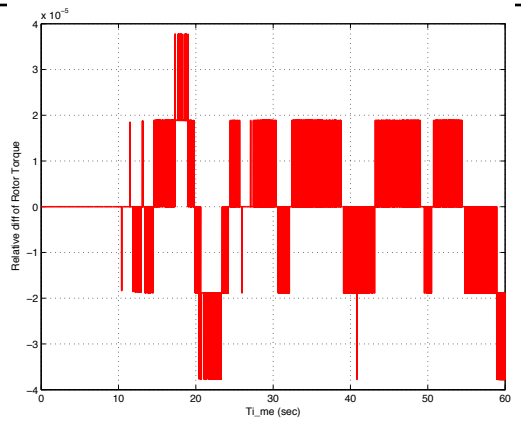



(d) Running time in Log-log scale plot

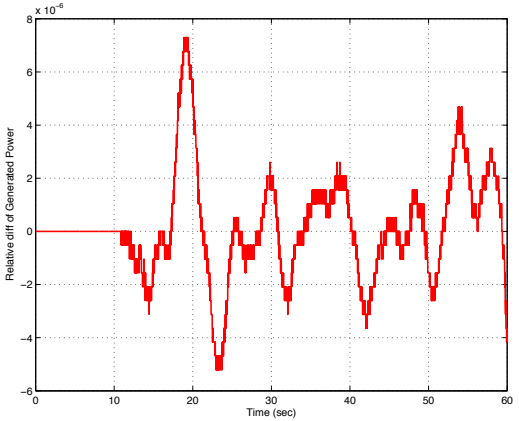
# Parallelized Treecode in Fortran



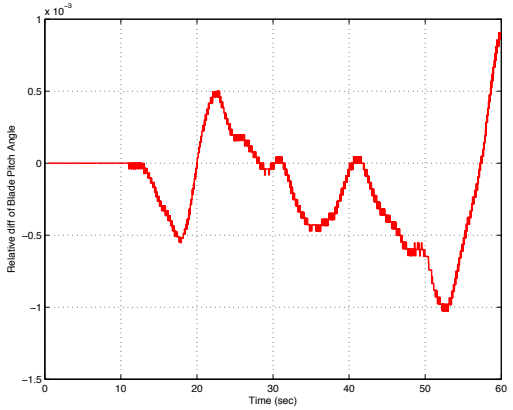

(a) Relative error of rotor speed




(b) Relative error of rotor torque




(c) Relative error of generated power




(d) Relative error of blade pitch angle

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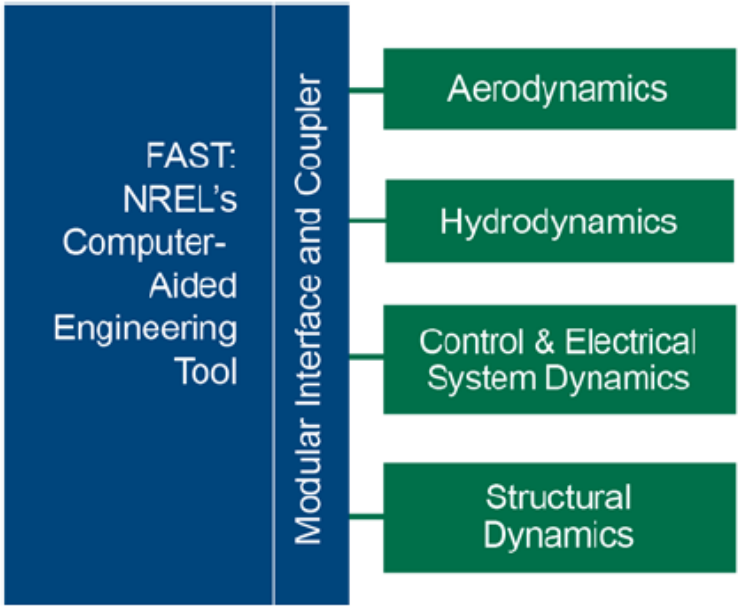
# New Framework of FAST

- New framework of FAST support
- WInDS is integrated into AeroDyn



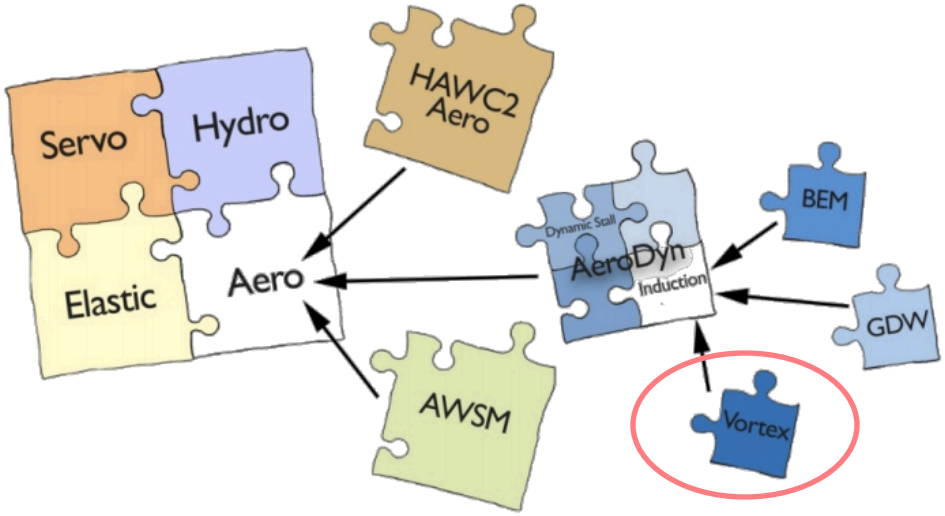
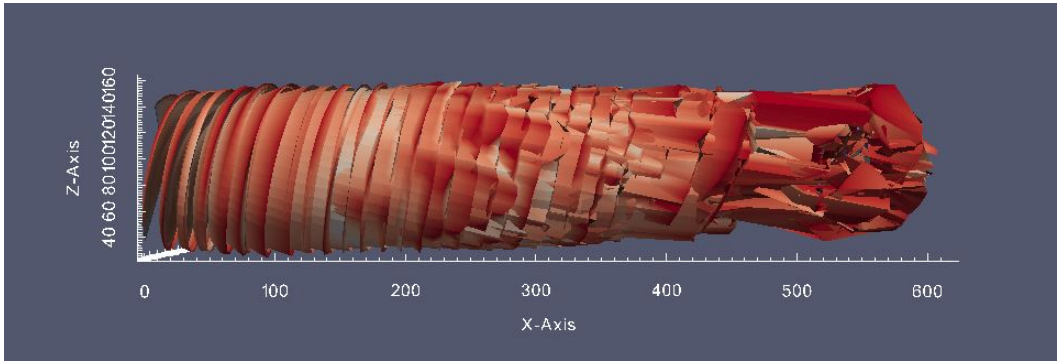
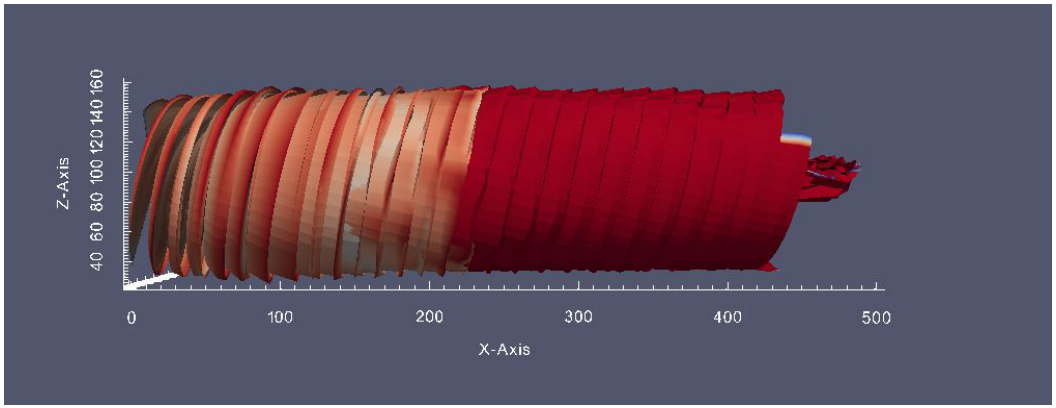




Figure Credit: NREL

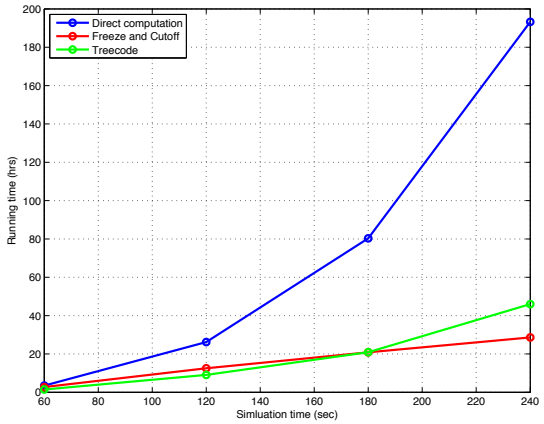
# Far Wake Approximation



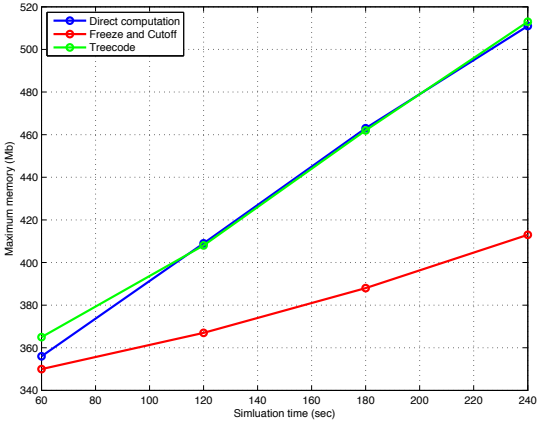




Full wake vs far wake approximation

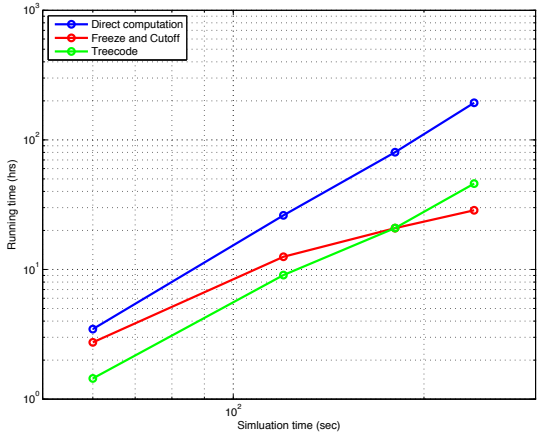
# Comparison of Computation Approaches



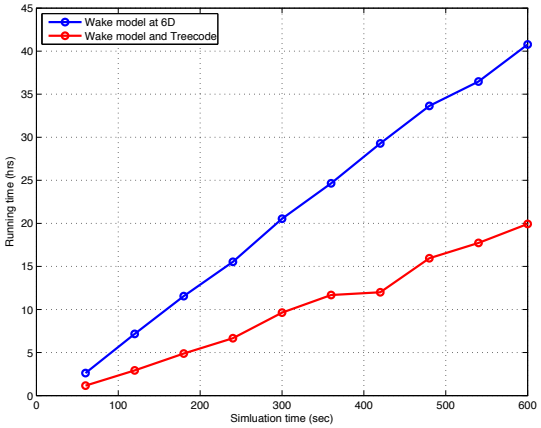

(a) Comparison of running time




(b) Comparison of max memory




(c) Comparison of running in log scale

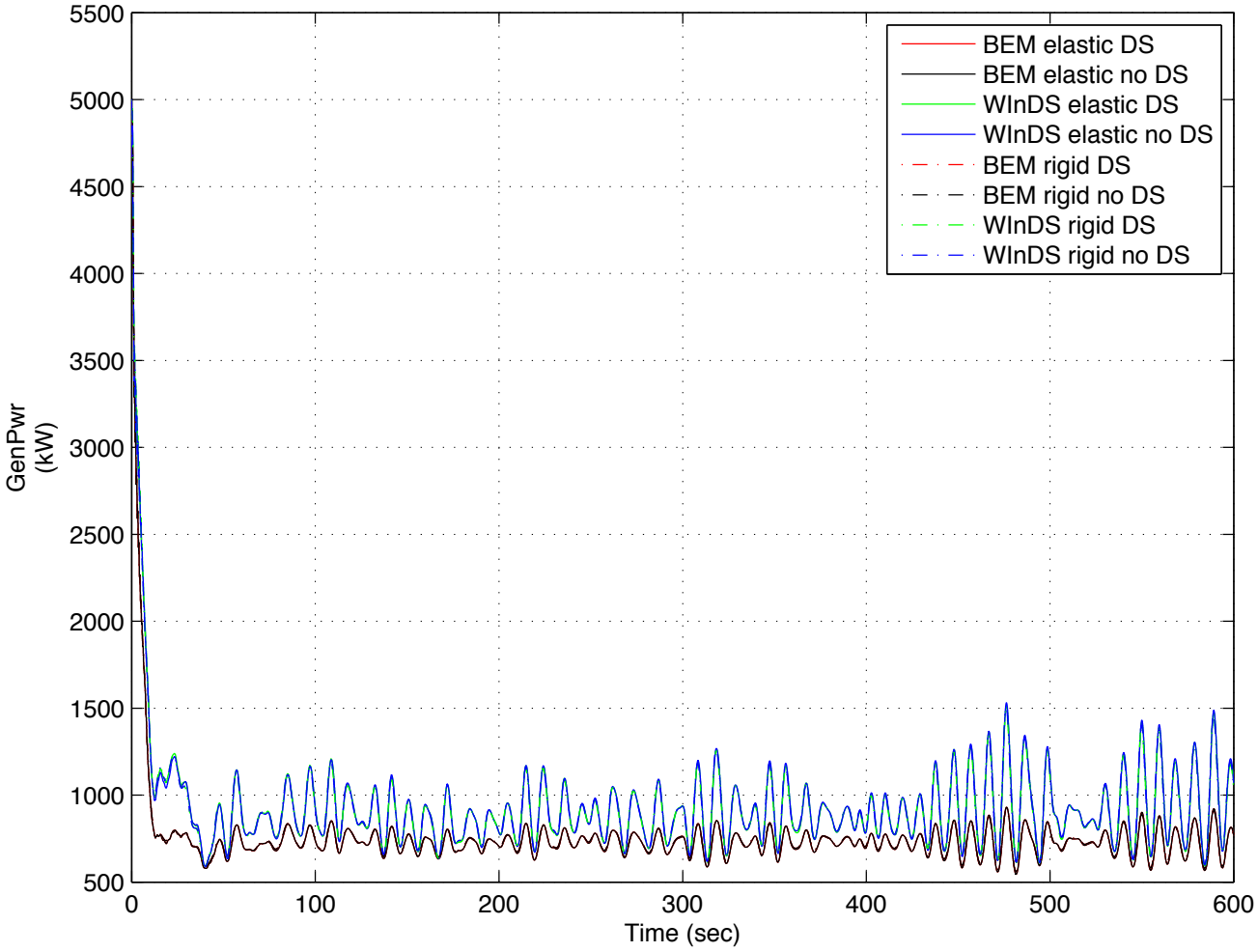



(d) Comparison of running time by two computation approaches

# Results

- Simulations of on NREL 5-MW offshore turbine + OC3 Hywind platform
- Outputs are generated power
- Applied parallelized Treecode Algorithm and far wake approximation
- Run on Massachusetts Green High Performance Computing Center (MGHPCC)

# Below Rated Inflow



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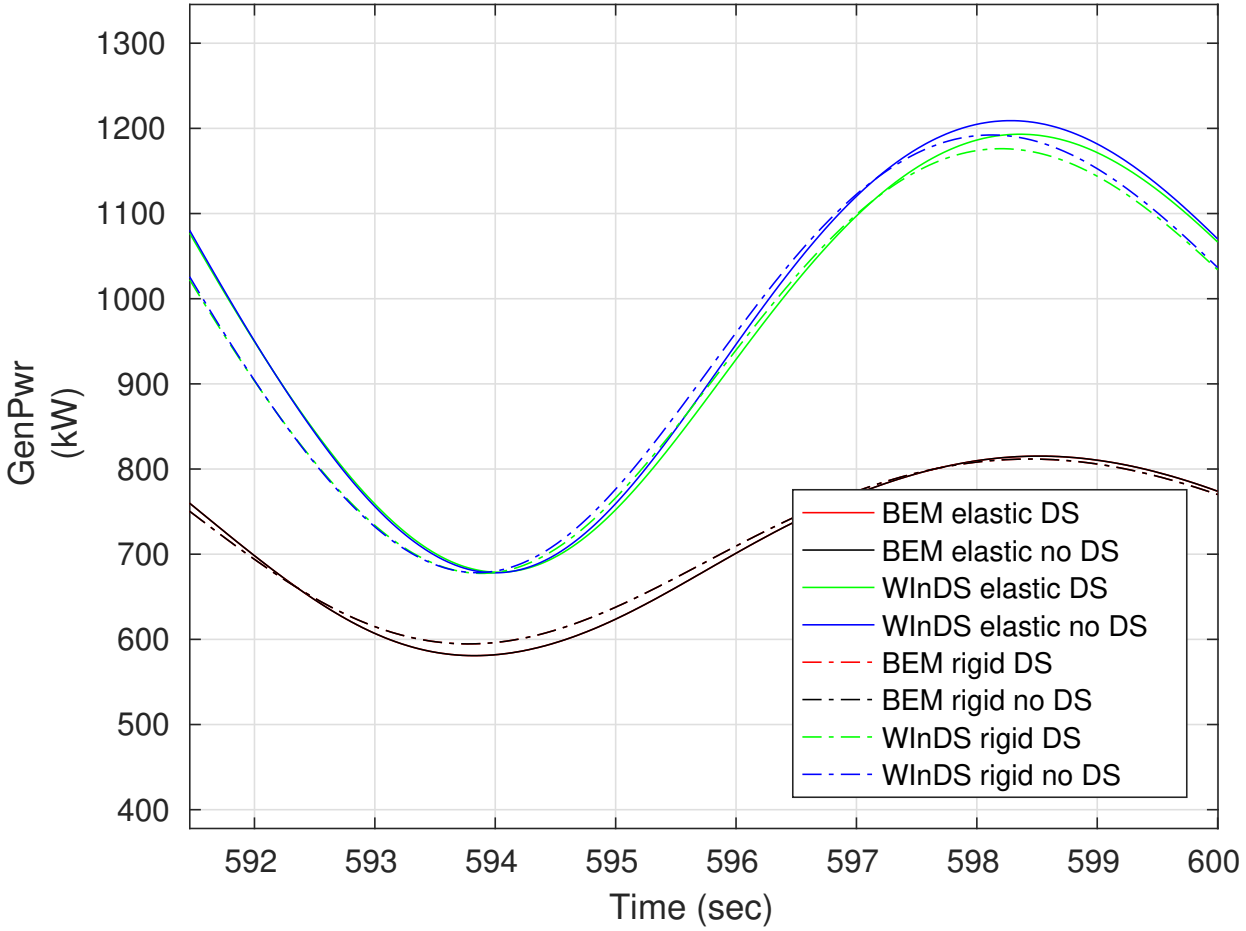
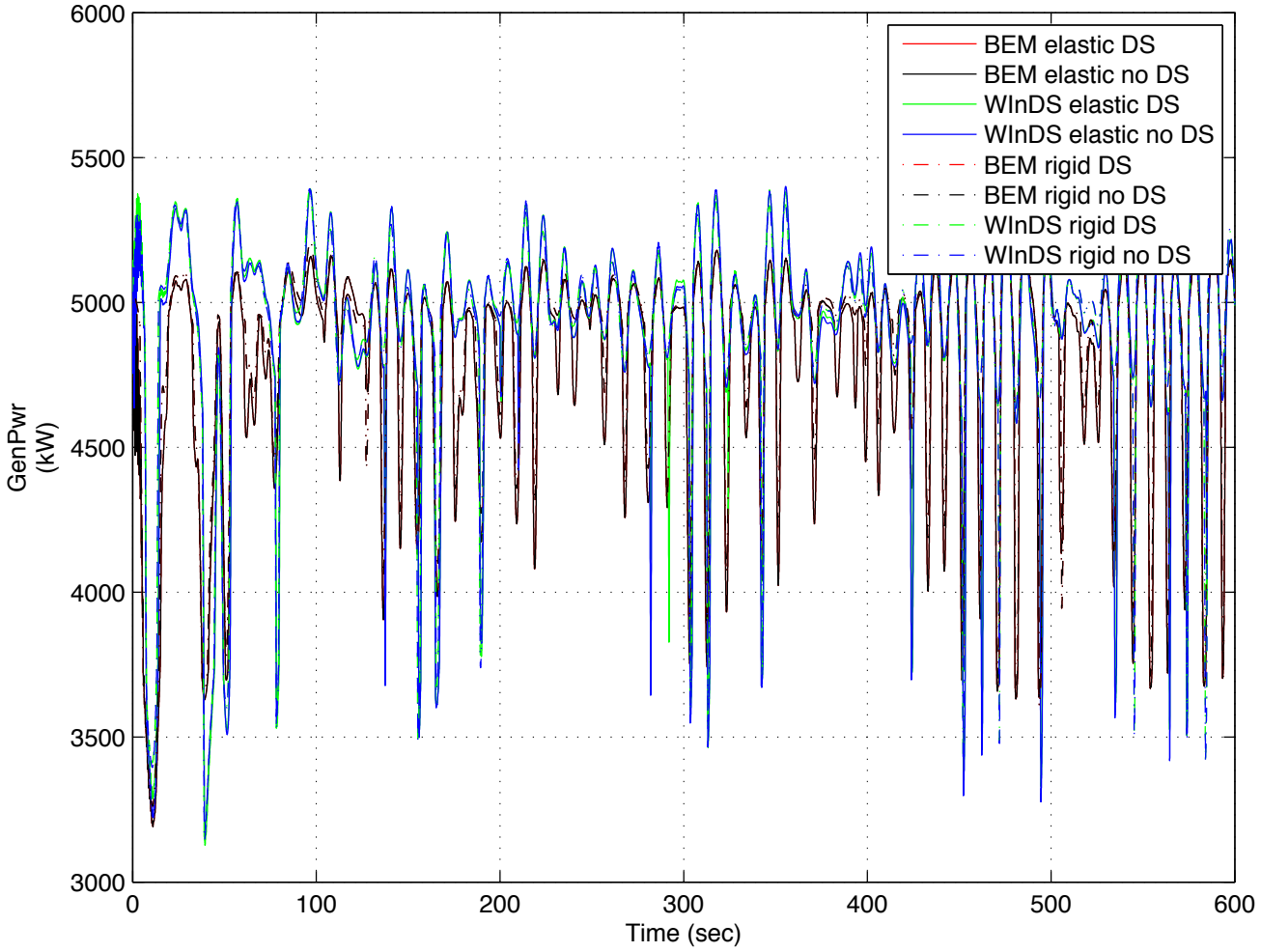
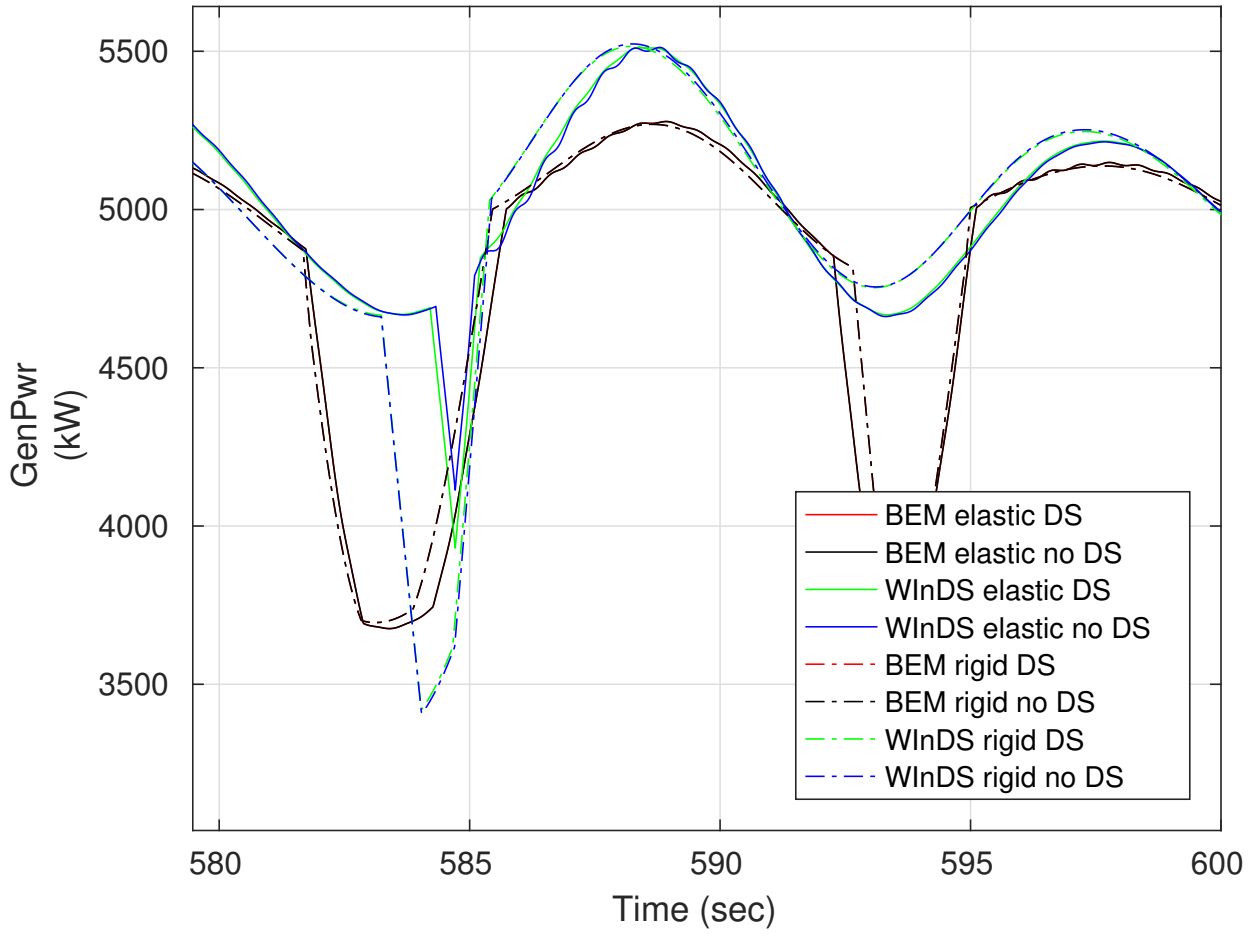


# Rated Inflow



# Rated Inflow



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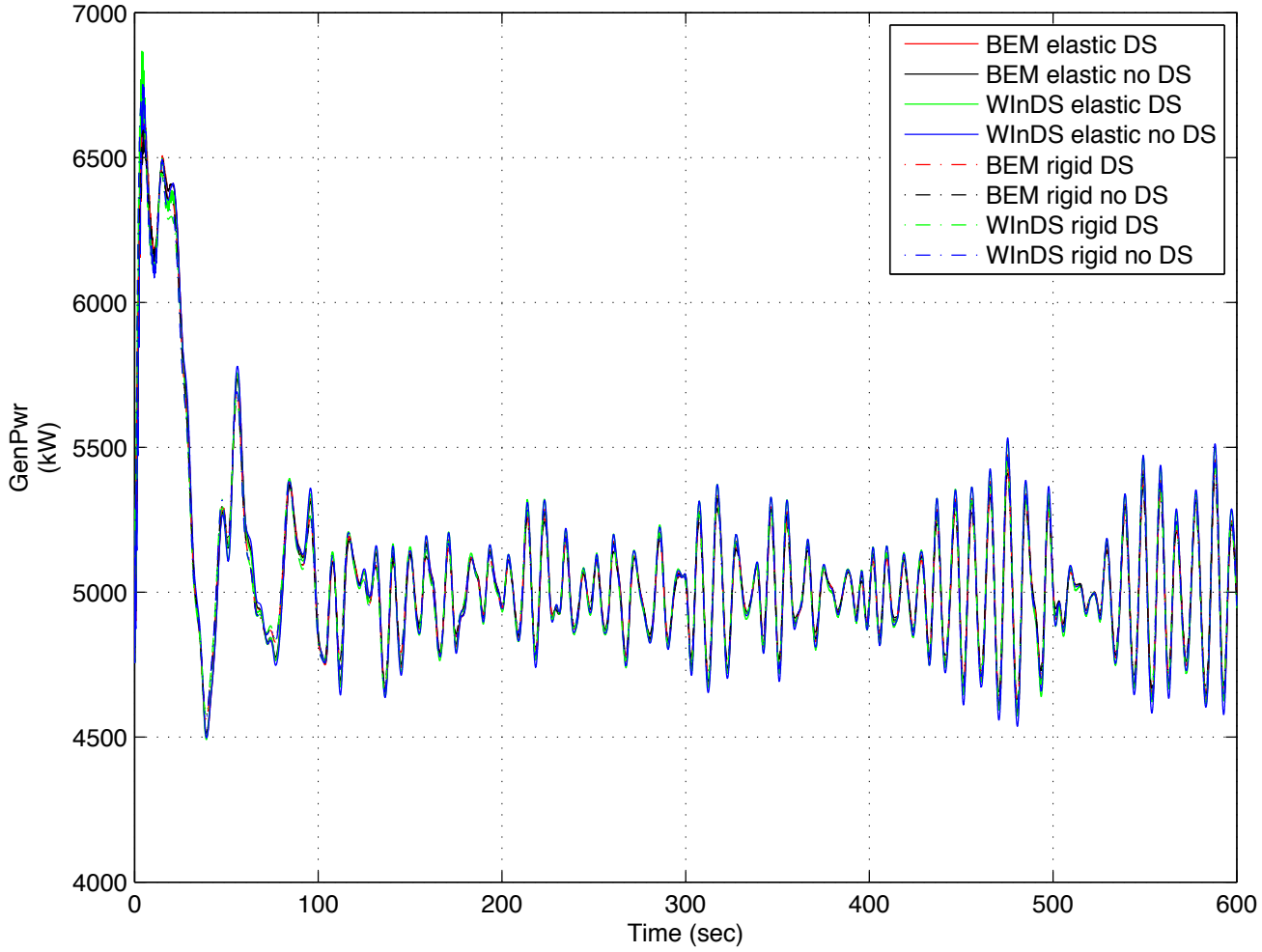

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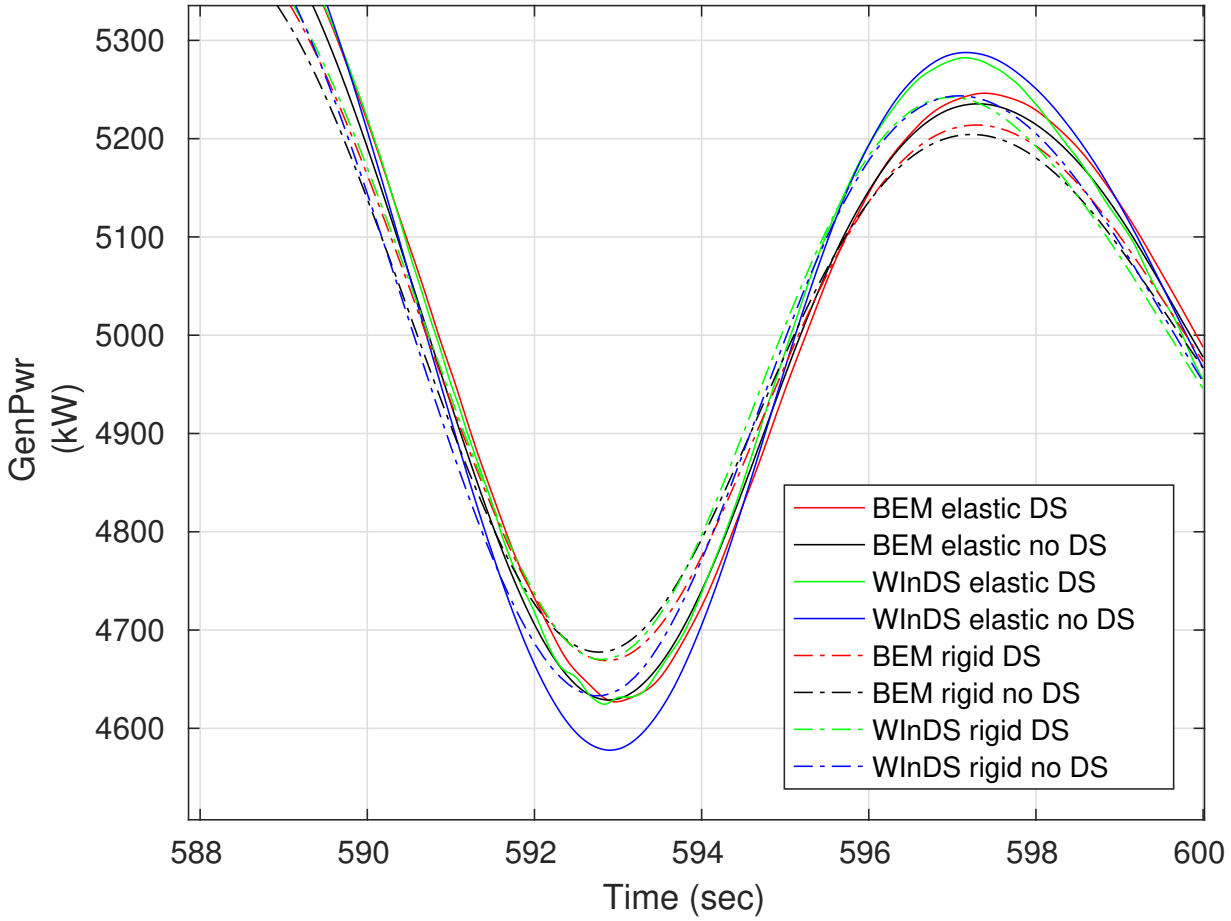

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# Near-Term Goals

- Run more simulations under different wave and wind conditions.
- Quantitatively analyze the influence of elasticity of floating wind turbine on unsteadiness of aerodynamics.
- Provide suggestions for OFWT design.
- Prepare for journal publication.
- Finish dissertation.

# Concluding Remarks

- Parallelized Treecode Algorithm has been used to speedup WInDS.
- WInDS has been re-written in Fortran and integrated with FAST to enable full aero-hydro-servo-elastic simulations.
- FAST/WInDS has been compiled in Linux for super-computing.
- WInDS has been shown to be more sensitive to the wave-driven platform motions than BEMT and have a higher level of accuracy.

# References


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- **Questions?**