



Cornell University

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# Wind Turbine Loads

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All figures/videos/tables are taken from the open domain internet and previous/current research. Figures/tables taken from other literature are clearly pointed out.



## ***Content***

- ❖ Wind Turbine Loads
  - Load types, sources and effects
- ❖ General Principles of Mechanics
  - Gyroscopic motion, single DOF systems, cantilevered beams
- ❖ Wind Turbine Dynamics
  - Wind turbine blade structural analysis, wind turbine dynamics
- ❖ Finite Element Method for Wind Turbine Analysis
  - Static analysis, natural frequency, fatigue, wind turbine design
- ❖ Wind Turbine Loads Induce Ground Vibration (New Research)
  - Hands-on test & data analysis



## *Wind Turbine Loads*

### ❖ Types of Loads

- Steady (static and rotating)
- Cyclic
- Transient
- Stochastic
- Resonance-induced loads



### ❖ Sources of Loads

- Aerodynamics
- Gravity
- Dynamic interactions
- Mechanical Control

### ❖ Effects of Loads

- Ultimate limit state
- Fatigue



# General Principles of Mechanics

## ❖ Gyroscopic Motion



MIT Professor Walter Lewi's wheel momentum video from Youtube

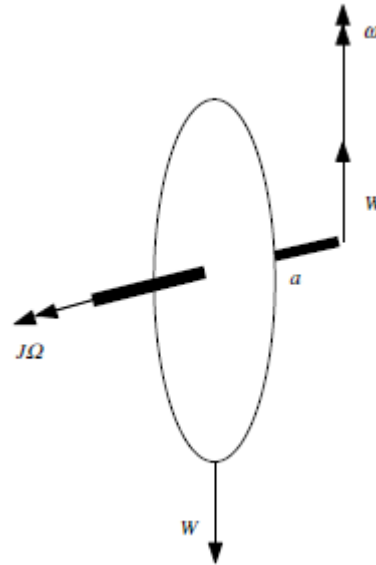


Figure 4.3 from Manwell Ch4

$$\sum M = W a = \omega \times J \Omega$$



Question:

What's the effect of gyroscopic load on wind turbine?

- A. Vertical force acts on the tower
- B. Bending moment acts to pitch the rotor
- C. Flapwise bending moment on blade root
- D. Twist the nacelle and tear down the turbine



# Vibration Basics

## ❖ Equation of Motion for Single DOF Systems

Four forces in a general equation of motion: inertial force, damping force, elastic force, and external force

$$m\ddot{x} + c\dot{x} + kx = F(t), \quad x(t=0) = x_0, \quad \dot{x}(t=0) = \dot{x}_0$$

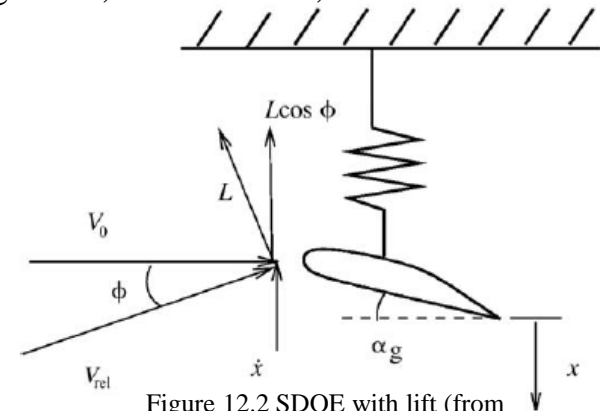
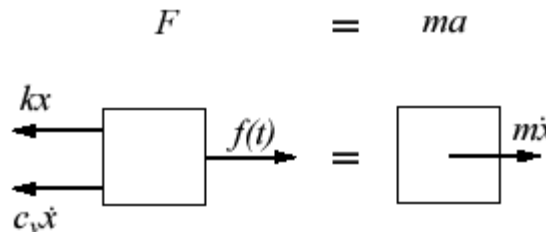
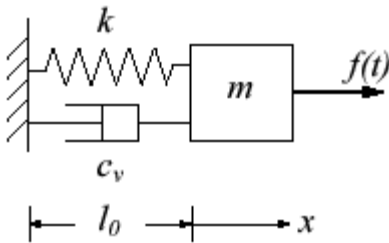


Figure 12.2 SDOE with lift (from Aerodynamics of Wind Turbines)

- Undamped vibration with no external force:  $m\ddot{x} + kx = 0$  (homogeneous linear ODE problem)

$$x = A \cos(\omega_n t) + B \sin(\omega_n t) \Rightarrow x = x_0 \cos(\omega_n t) + \frac{\dot{x}_0}{\omega_n} \sin(\omega_n t)$$

- Damped vibration with no external force:  $m\ddot{x} + c\dot{x} + kx = 0$  (homogeneous linear ODE problem)
- Damped vibration with harmonic external force:  $m\ddot{x} + c\dot{x} + kx = F_0 \sin(\omega t)$  (non-homogeneous linear ODE problem)



# Vibration Basics

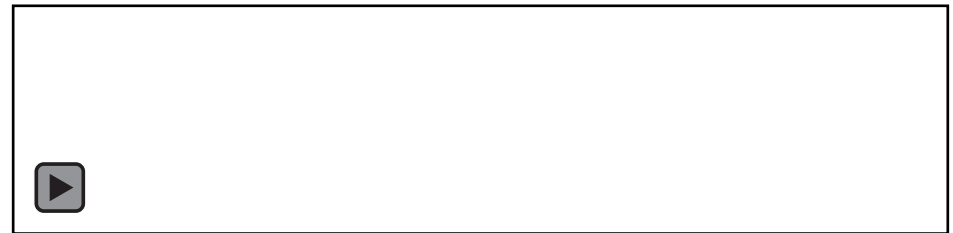
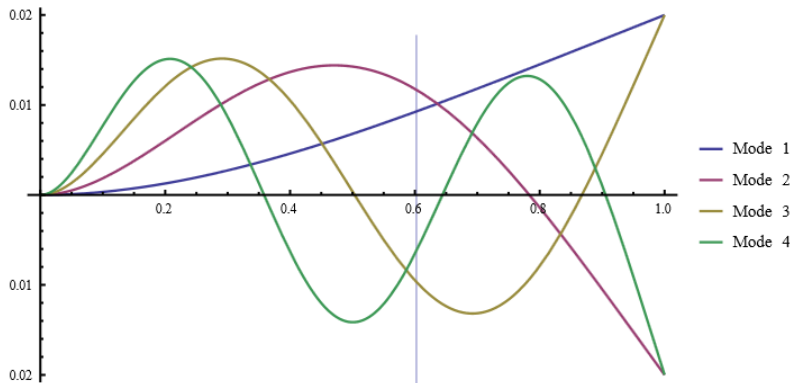
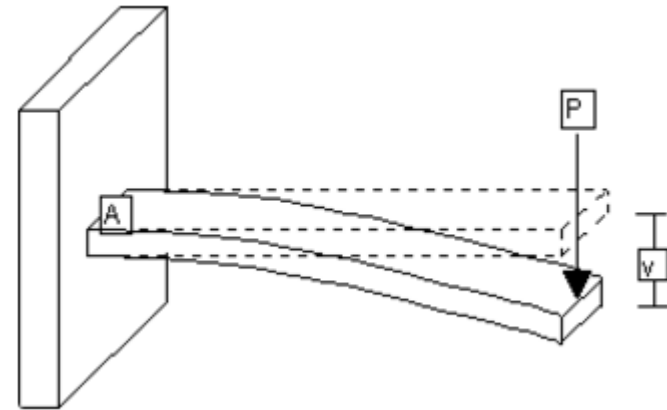
- ❖ Cantilevered beams
- ❖ Euler-Lagrange Equation of Euler-Bernoulli Beam

$$\frac{\partial^2}{\partial x^2} \left( EI \frac{\partial^2 w}{\partial x^2} \right) = -\mu \frac{\partial^2 w}{\partial t^2} + q(x)$$

- ❖ Free vibration (no  $q(x)$ )

$$w_n = A_1 \cosh(\beta_n x) + A_2 \sinh(\beta_n x) + A_3 \cos(\beta_n x) + A_4 \sin(\beta_n x), \quad \beta_n = \left( \frac{\mu \omega_n^2}{EI} \right)^{1/4}$$

- ❖ Mode: each displacement solution under natural frequency  $\omega_n$





# Wind Turbine Blade Structural Analysis

## ❖ Flapwise Bending Moments and Stress

$$T = C_T \frac{1}{2} \rho \pi R^2 U^2, \quad C_T = \frac{8}{9} \text{ for ideal rotor}$$

$$M_\beta = \frac{1}{B} \int_0^R r \left( \frac{1}{2} \rho \pi \frac{8}{9} U^2 2r dr \right) = \frac{T}{B} \frac{2}{3} R$$

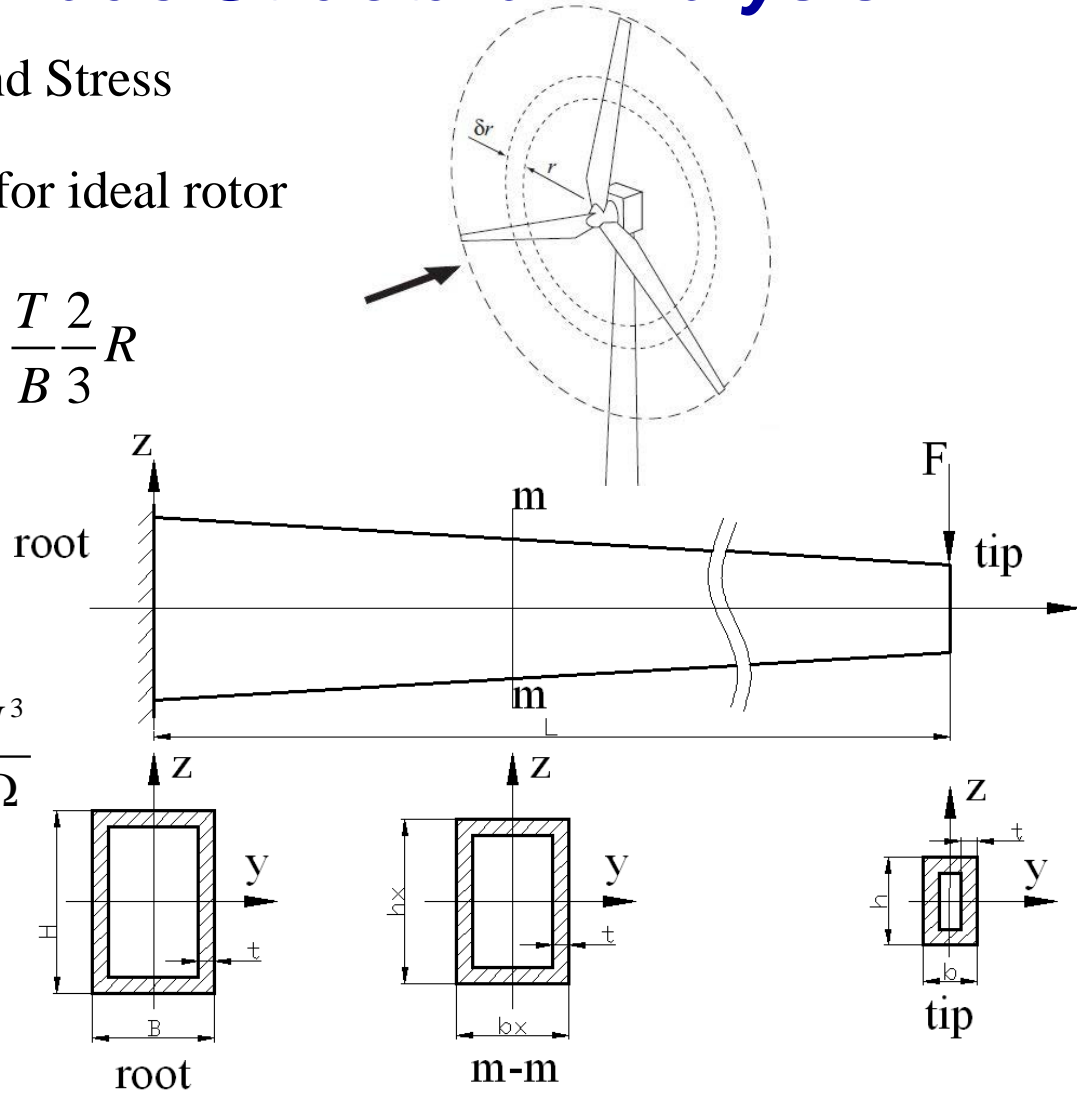
$$\sigma_{\beta, \max} = M_\beta c / I_b$$

## ❖ Edgewise Forces and Moments

$$Q = \frac{P}{\Omega} = \frac{1}{\Omega} \frac{16}{27} \frac{1}{2} \rho \pi R^2 U^3 = \frac{8}{27} \rho \pi R^2 \frac{U^3}{\Omega}$$

$$M = Q / B$$

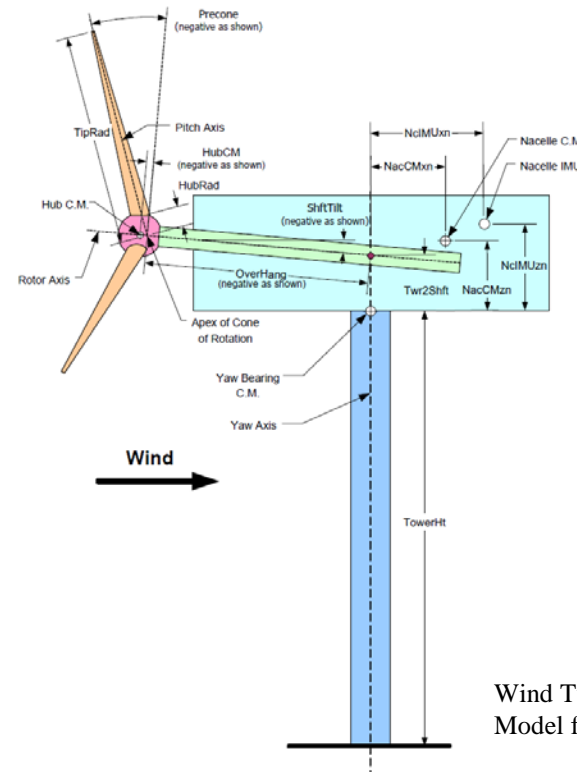
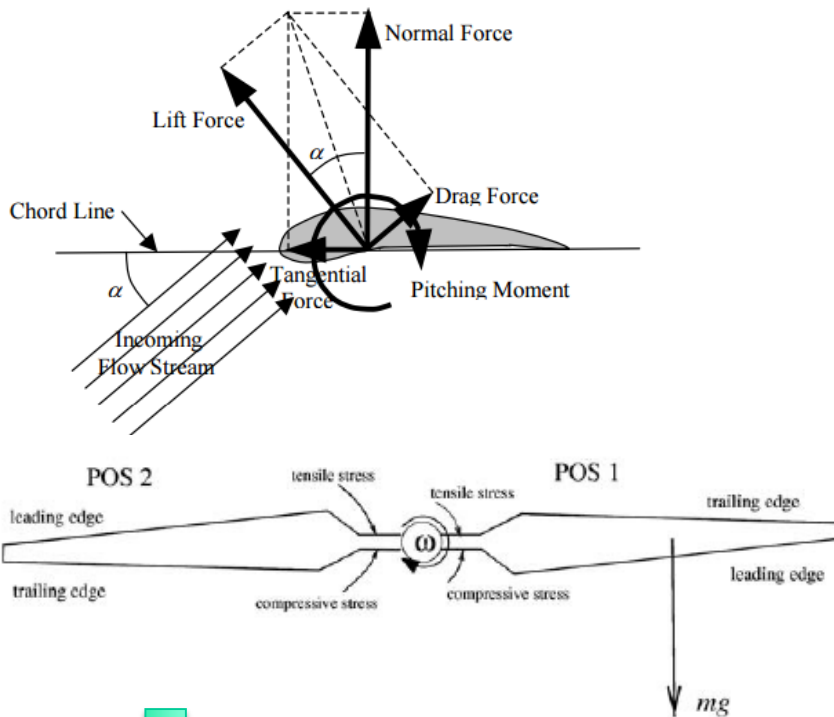
$$S = \int_0^R dF_T$$





# Wind Turbine Dynamics - Introduction

❖ From Wind Turbine Loads to Wind Turbine Dynamics



Wind Turbine Dynamic Model from NREL FAST

Skip Many Equations .....

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{k}\mathbf{x} = \mathbf{F}$$

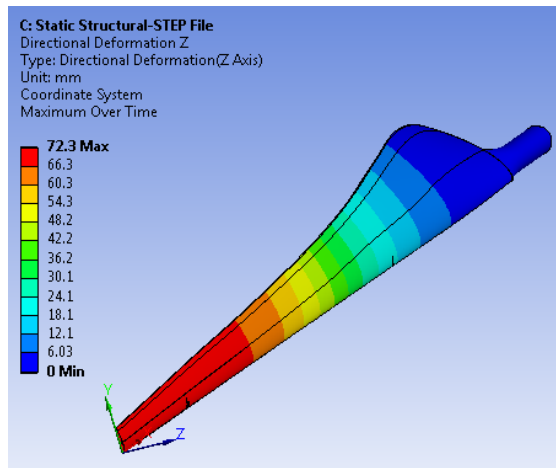


Displacement, acceleration, force, stress, natural frequency, .....

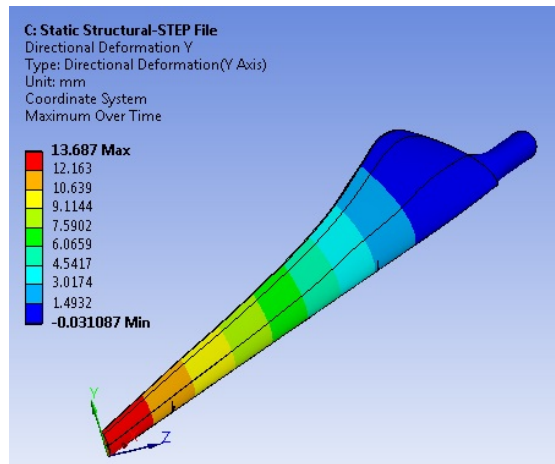


# Finite Element Method for Wind Turbine Structure Analysis

## ❖ Blade Static Structural Analysis



Flapwise deflection



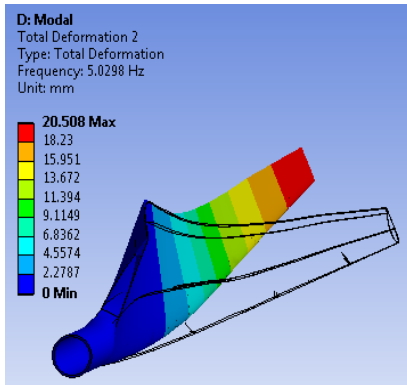
Edgewise deflection

		Current Blade	Reference Blade (Perkins and Cromack,1978)
Tip Deflection (mm)	Flapwise	13.69	14.5
	Edgewise	72.3	76
Maximum Bending Stress (MPa)	Top Surface (compression)	-3.73	-3.88
	Bottom Surface (tensile)	+3.26	+3.21

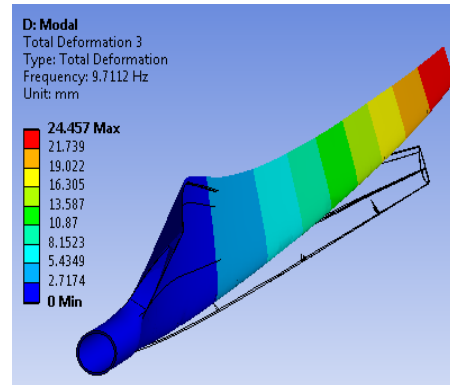


# Finite Element Method for Wind Turbine Structure Analysis

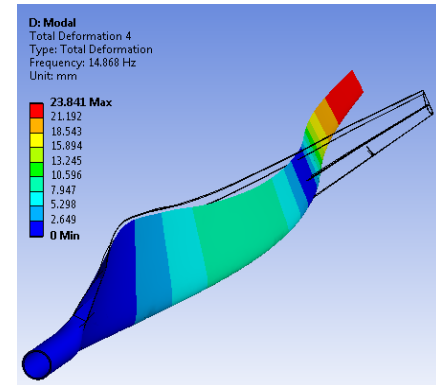
## ❖ Blade Natural Frequency Analysis



Mode I



Mode II



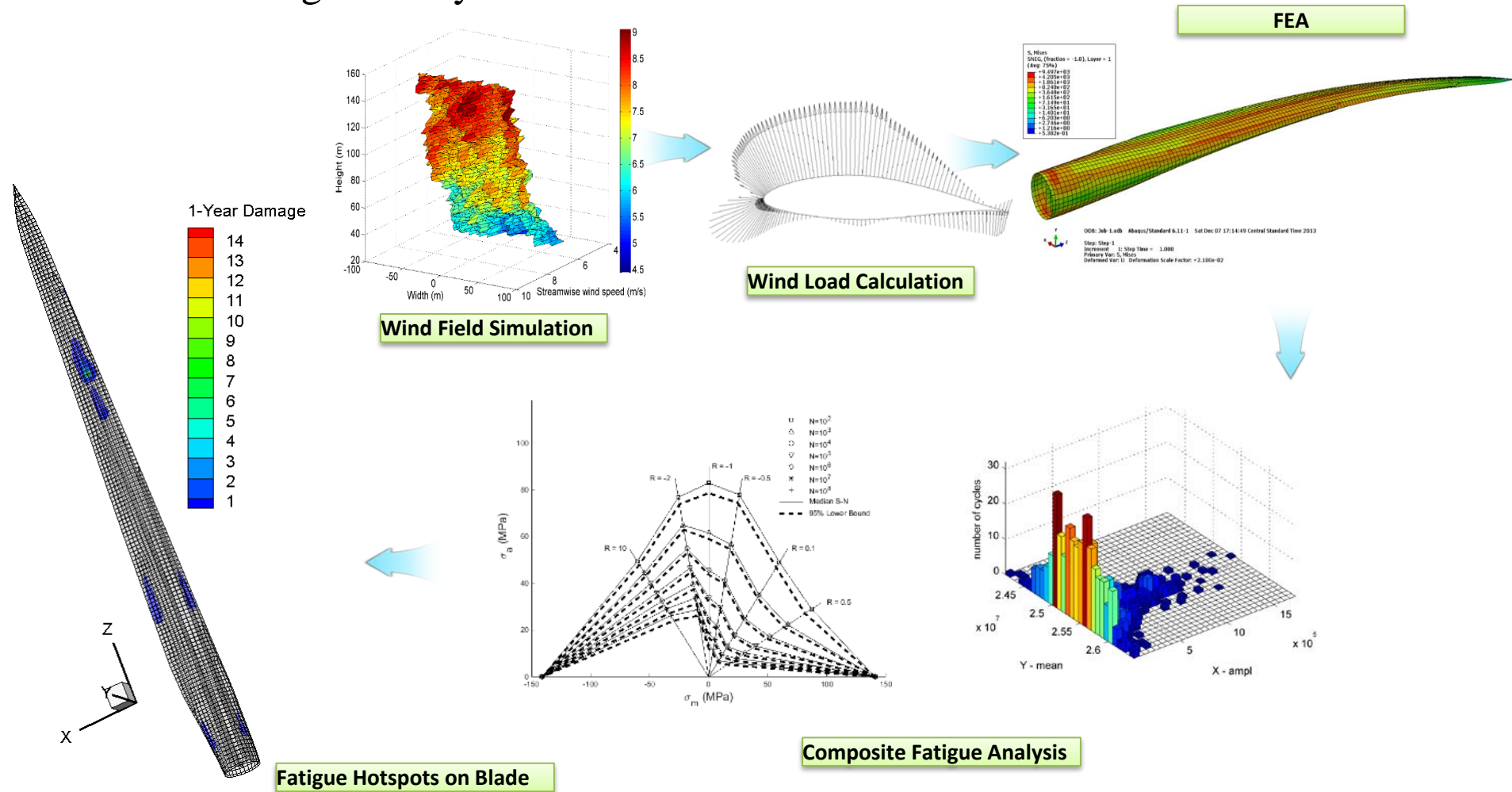
Mode III

Mode		Natural frequency		
		FEA Results	From Perkins and Cromack (1978)	
			Measured Results	Analytical Results
I	Flapwise	5.03 Hz	3.98 Hz	4.46 Hz
II	Edgewise	9.71 Hz	8.91 Hz	10.35 Hz
III	Flapwise	14.87 Hz	13.37 Hz	14.80 Hz



# Applying Wind Turbine Loads on Blade Fatigue Analysis

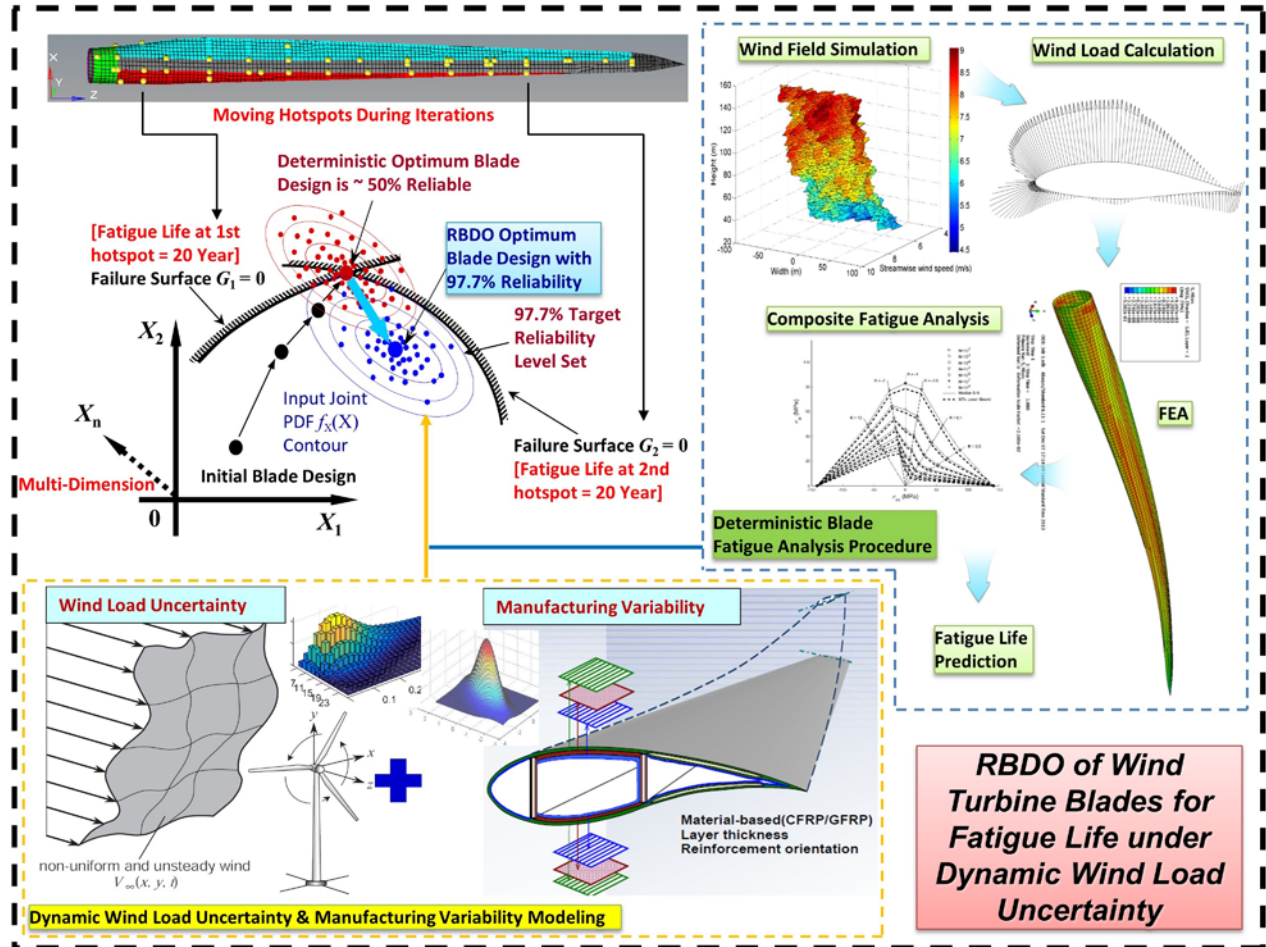
## ❖ Blade Fatigue Analysis Procedure





# Development of Uncertain Wind Load for Blade Design

Renewable Energy Global Innovations (REGI)  
Featured Article  
(web link:  
<https://reginnovations.org/wind-energy/reliability-based-design-optimization-wind-turbine-to-reduce-levelized-cost-energy/>)





# ***Wind Turbine Loads Induce Ground Vibration***

## ❖ Wind Loads, Wind Turbine Vibration, and Ground Vibration



### ❑ Class Experiment:

- ✓ Use a smartphone as a seismometer

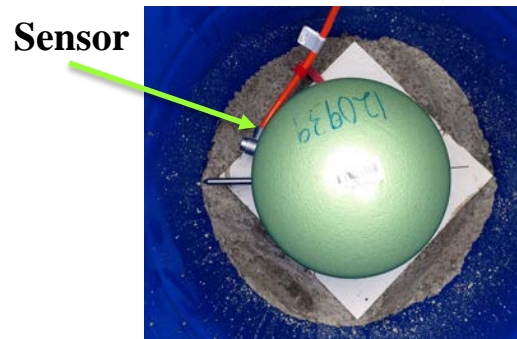
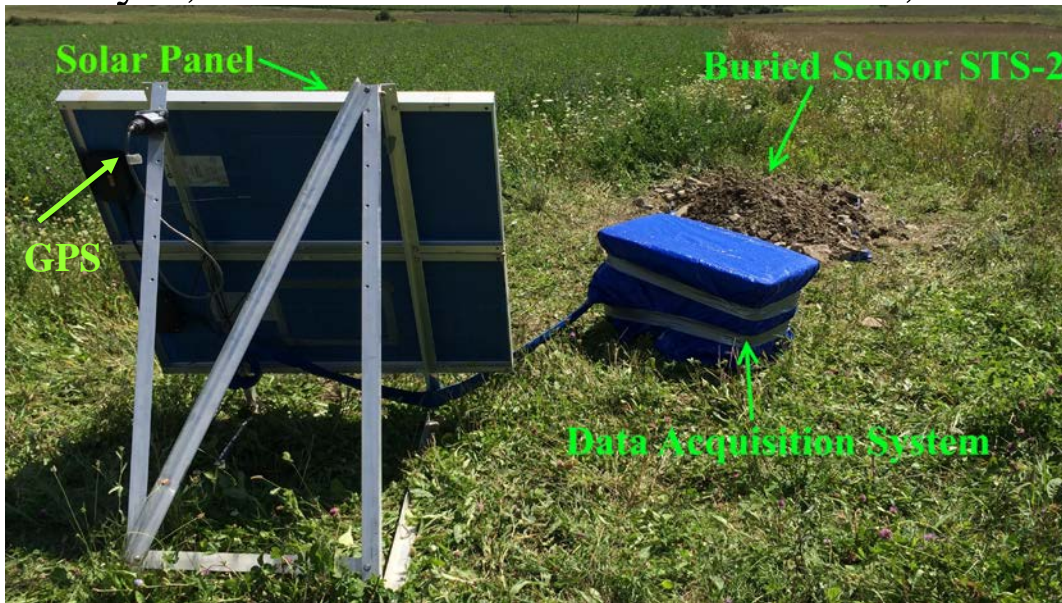


A turbine topples in wind gusts, Coldingham, Berwickshire, UK, 2011.  
Information found online.



## Wind Turbine Loads Induce Ground Vibration

- ❖ Collect Data of Ground Vibration Induced by Wind Turbines (Professor Sara C. Pryor, Professor Rebecca J. Barthelmie, Dr. Fred Letson, and Dr. Weifei Hu)



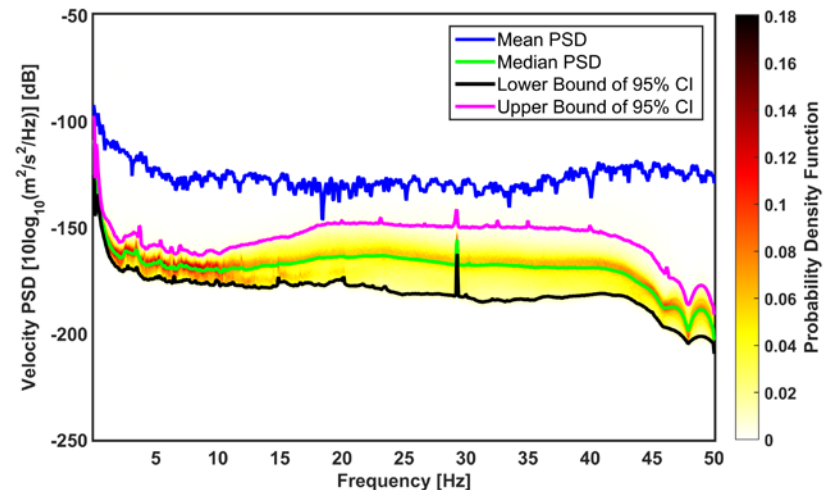
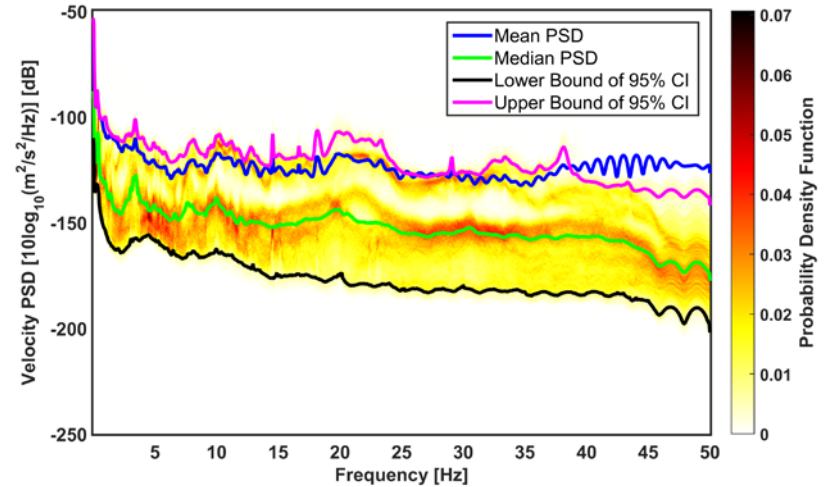
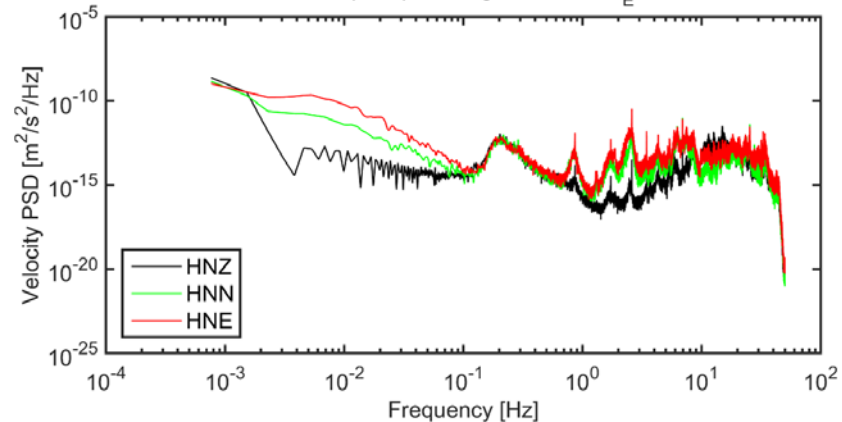
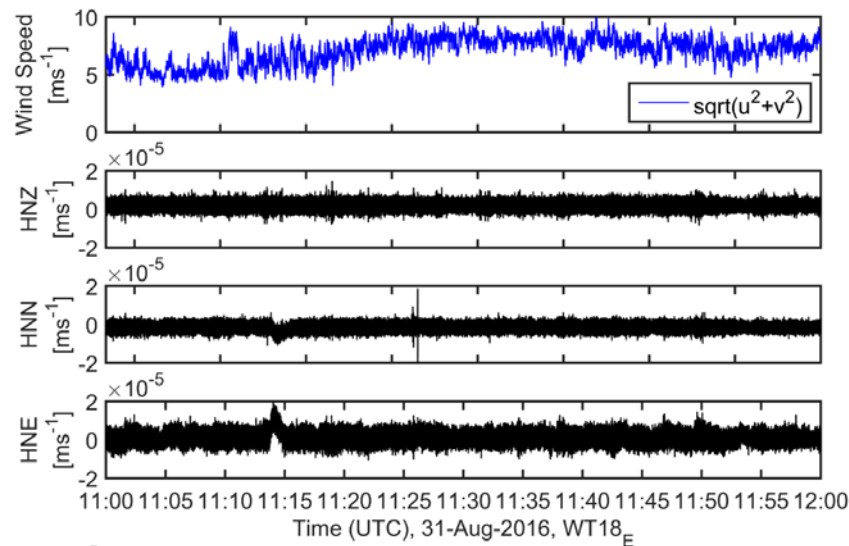
DAS Power Box Battery





# Wind Turbine Loads Induce Ground Vibration

❖ Significant Wind Turbine Signature Is Detected in Ground Vibration





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Thank You  
Q & A