Performance Simulation
of
Tethered Rotor-Blade Lifting Vehicles

Airborne Wind Energy Conference

September 29, 2010

Presentation Objectives:

- *for the 'Rotor Naïve'*
- *for the 'Rotor Aware'*
- *for the 'Rotor-head'*

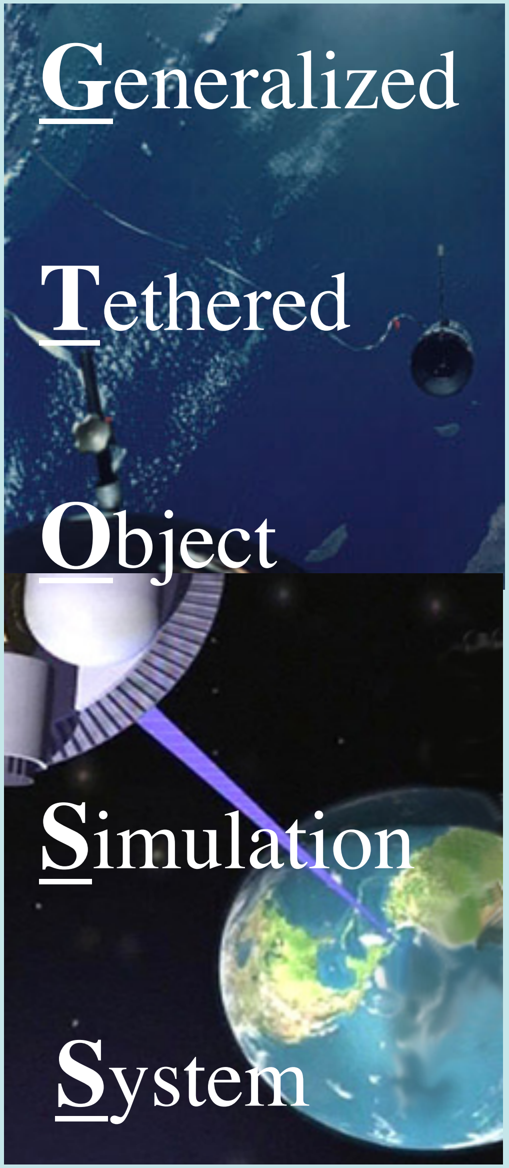
Subjects to be Addressed

- Applying Rotors to AWE as a Lift Element
- Modeling Tools Required
- Introduction to Rotor Idiosyncracies
- Modeling Rotor Lift
- Performance Simulation Example

Harvesting Wind Energy
with
Rotating Blade Lift Elements

- Pull Hard on a String - “Ground-Gen”
- Carry a Generator Aloft - “Air-Gen”
- Use Excess Autorotation Torque - “Air-Gen”
- Hybrid - Air-Gens using Turbines as multi-purpose

Modeling Tool

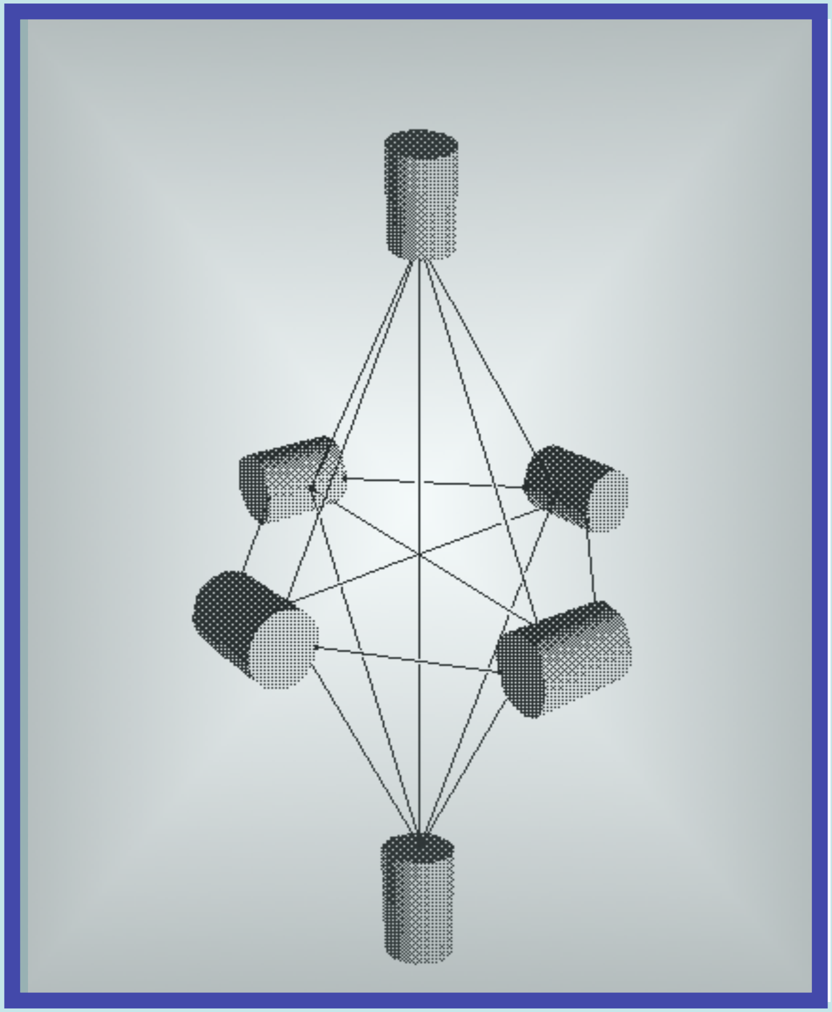


- **Point-Synthesis Finite Tether models, providing:**

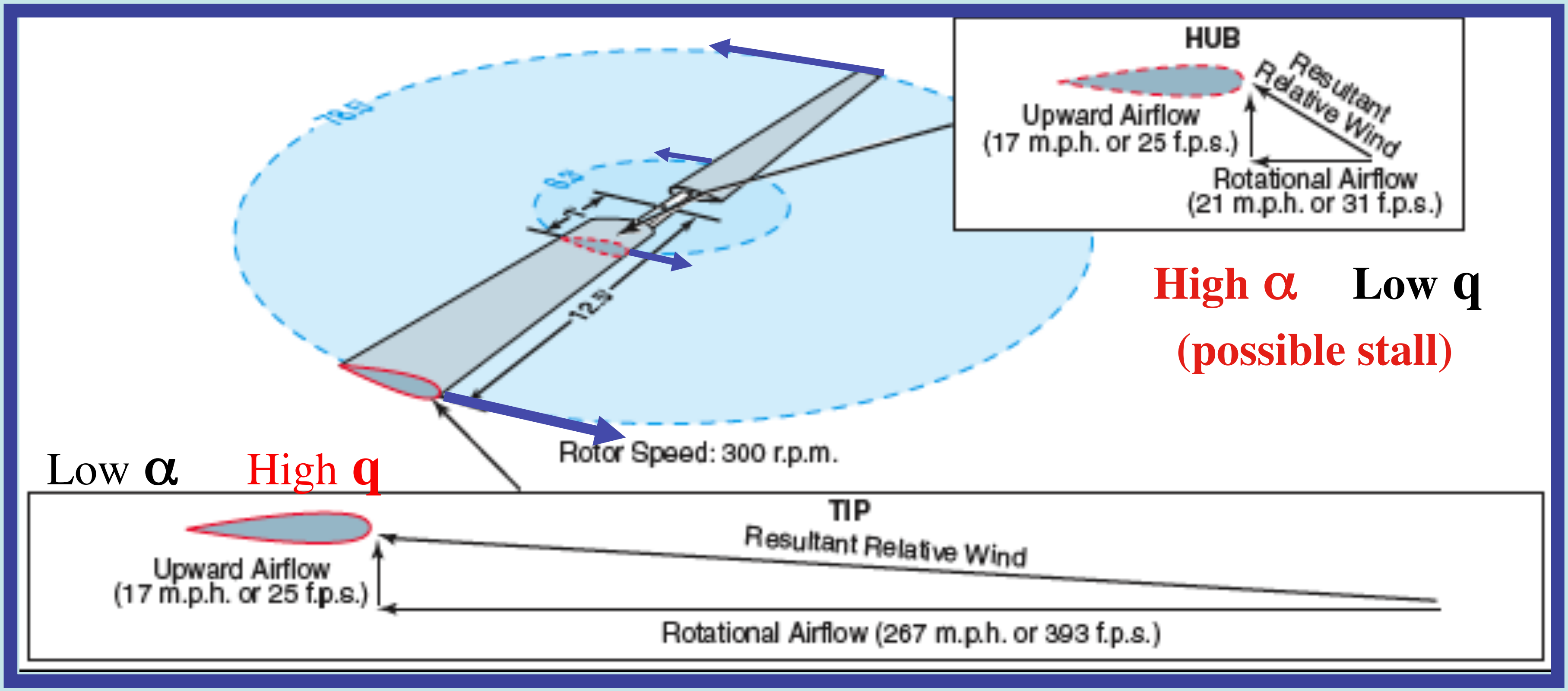
  Free or Constrained
  Tether Deployment-dynamics
  Non-Uniform Tethers
  Aero-dynamics
  Thermo-dynamics
  Electro-dynamics

- **Wind and Gust Atmospherics**
- **Industry Vetted**
- **User-friendly F99 code & Docs**
- **Multiple 6 DOF Bodies w/Arbitrary Tether Connectivity**

Example of General Connectivity



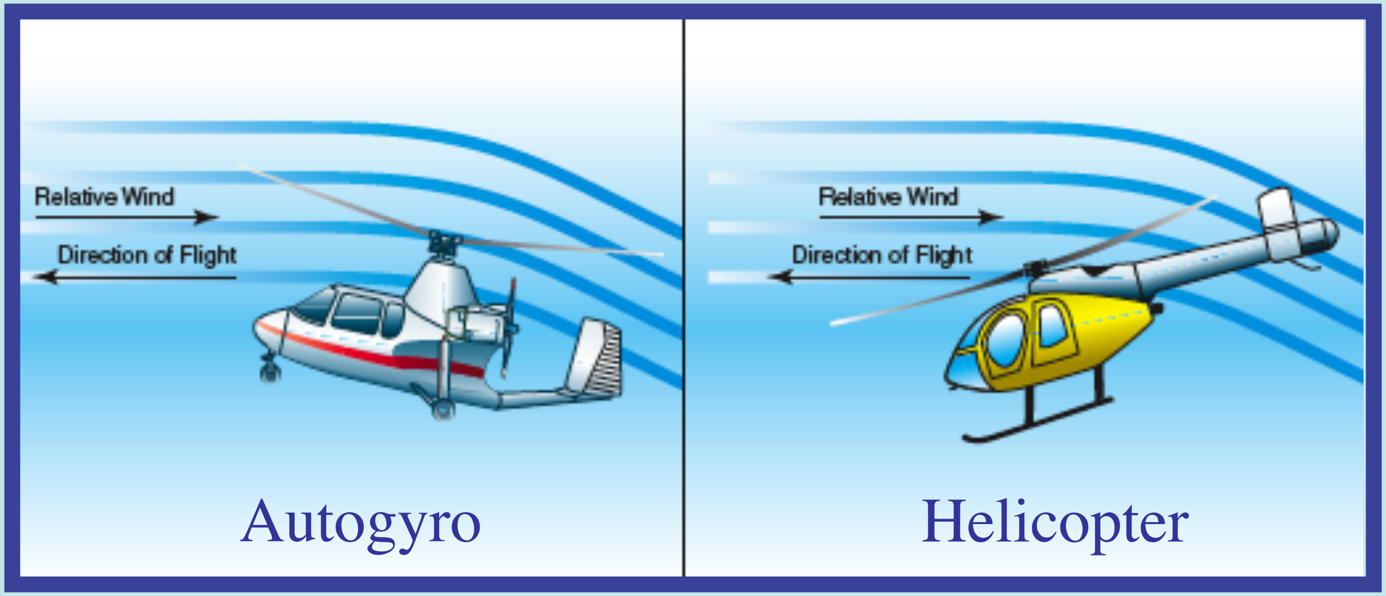
What a Rotor Blade Sees



Autogyro - vs - Helicopter

#1

- Inflow is From Opposite Direction -



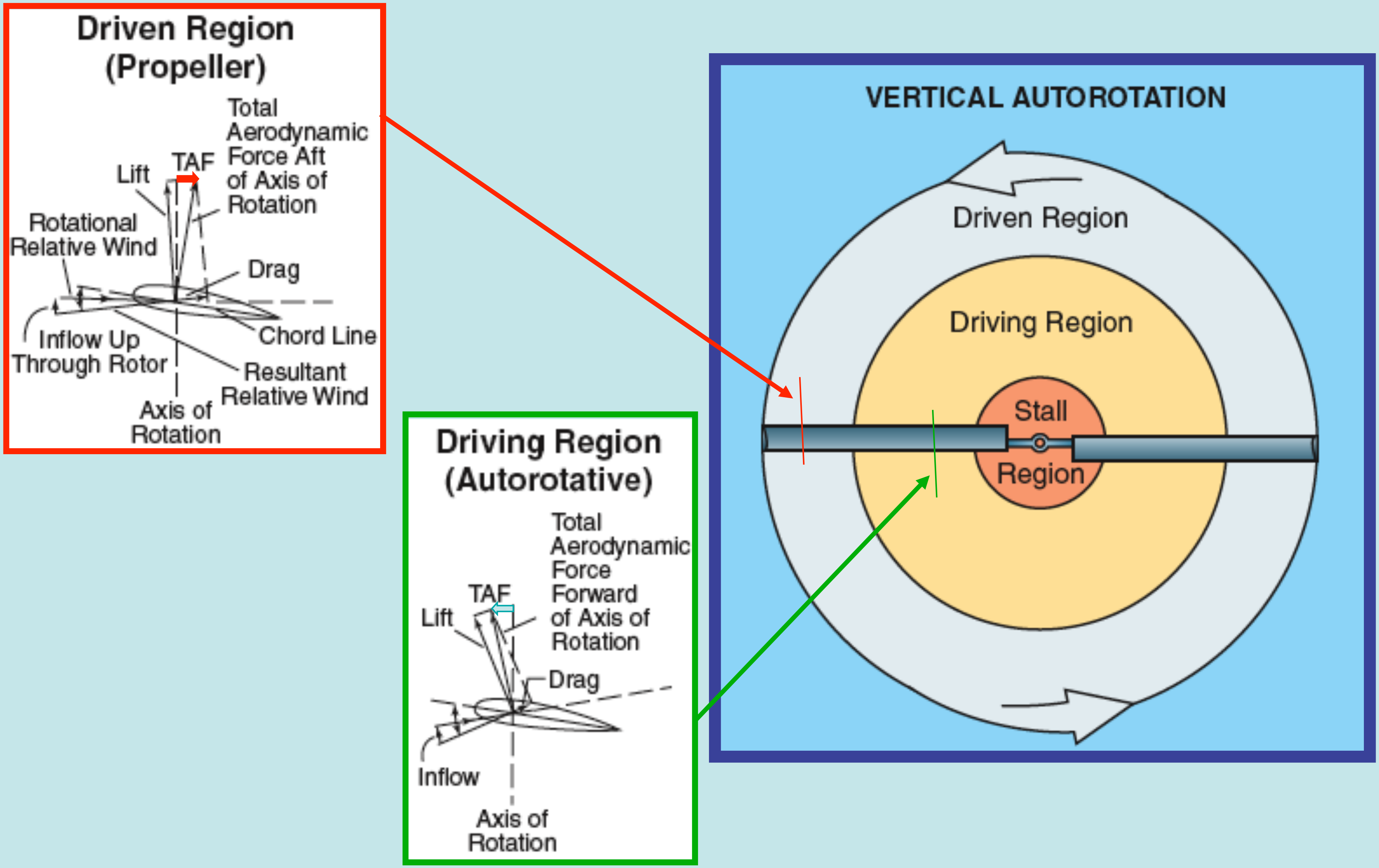
#2

- ***Autogyro Blades Power their own Rotation***

-vs-

- Helicopter Must Supply Power for Rotation

How Does Autorotation Occur



Putting Auto-Rotation to Work

- What Happens when Autogyro is Constrained by a Tether?

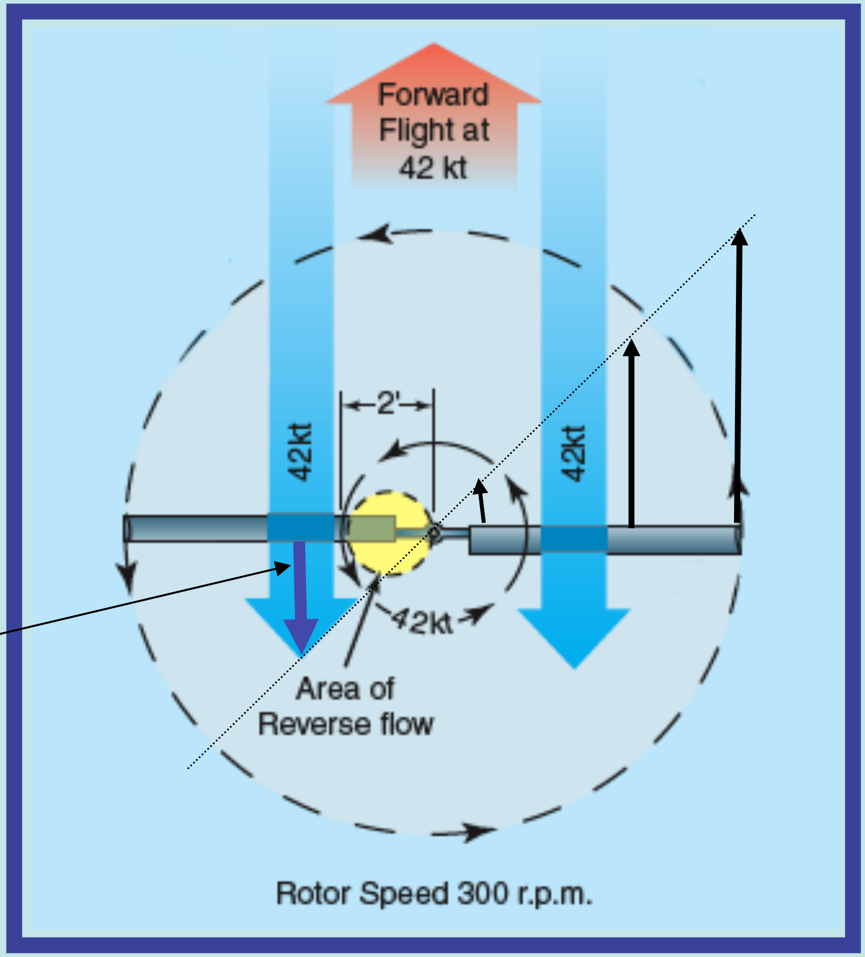
  - Changes how Autogyro functions compared to Free-flight

  - Can Experience *Large Impinging Relative Wind* Velocities

  - ***Steady-State*** Disk-Loading can **Exceed** *Normal Free Flight*

➡ RPM is King! ⬅

The Problem With Rotors



$V_{rot} = r\Omega$

Tip Speed Advancement Ratio "μ"

μ = (Impinging Wind-speed) / (R Ω)

The Impact of Relative Wind

- Wind **Powers** the Autorotation, thus, LIFT
- Wind can produce **Stall regions** in the Rotor
- Creates Complex Blade Aerodynamic Environ.
  - function of Impinging Wind Level and Direction
  - function of RPM
  - function of Radial Position along a Blade
  - function of a Blade's Azimuth Position

Rotor-Map Schemes

- **Pros:** Reduces High CPU Cost
  - can be useful for "Real Time" applications
  - can minimize "Development" execution run-times †

- **Cons:** Labor-Intensive Up Front Costs
  - Unwieldy for Blade Configuration Changes
  - Complexity as Function of Independent Parameters
  - Easy to Exceed "Envelope" in AWE Simulation

- **Can be Problematic for AWE Exploration**

➡ **An Observation**:

Developed via Blade Element Simulations

Blade Element Model

- Element-by-Element Modeling (*for each Blade*):
  - *Incident Flow* = ***f****(radius, azimuth, RPM, incident wind)*
  - *Induced Flow* = ***f****(airload, radius, azimuth)*
  - Specific 2-D Airfoil section = ***f****(radius)*
  - Chord-width = ***f****(radius)*
  - Blade Differential-Twist = ***f****(radius)*
  - Blade "Collective" and "Cyclic" *(control parameters)*
- 2-D Aero Coefficients table-driven -vs- AOA & Mach
  - Requires wide-range aero data ("C81 tables")

Inflow "Corrections"

- Why Needed
- Dynamic -vs- Quasi-Steady Induced-flow Models
- "QUASI-STEADY" Models
  - "Glauert Correction"

    $$v_i = v_{io} \, [1 + r' \, K \cos(\Psi_R) \,]$$

    where: v_{io} is aver. "momentum-theory velocity"
    r' is x/R
    K ranges from 0.5 - 1.6
- "DYNAMIC" Models
  - Numerous models have been developed
  - Murakami & Houston - specific to Auto-rotation

Tip Corrections

- Why Needed for the Blade Element Model

  - 2-D Aero data predicts Thrust

    BUT

  - Flow near Blade Tips reflect 3-D phenomenon

    ⇨ Vortex Interactions

    ⇨ Radial Flow

- *Complex* Corrections by Prandtl (and others)

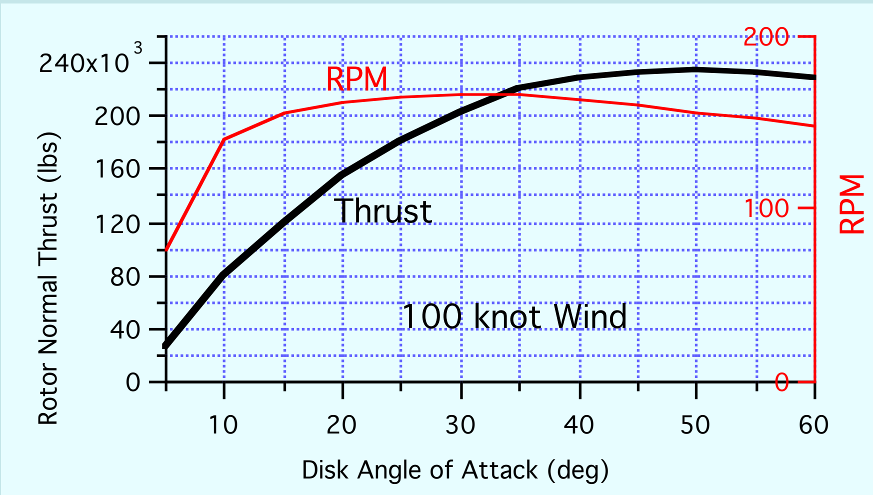
- *Simple* Correction: if $r/R > K_{tip}$ then, **Lift = 0**

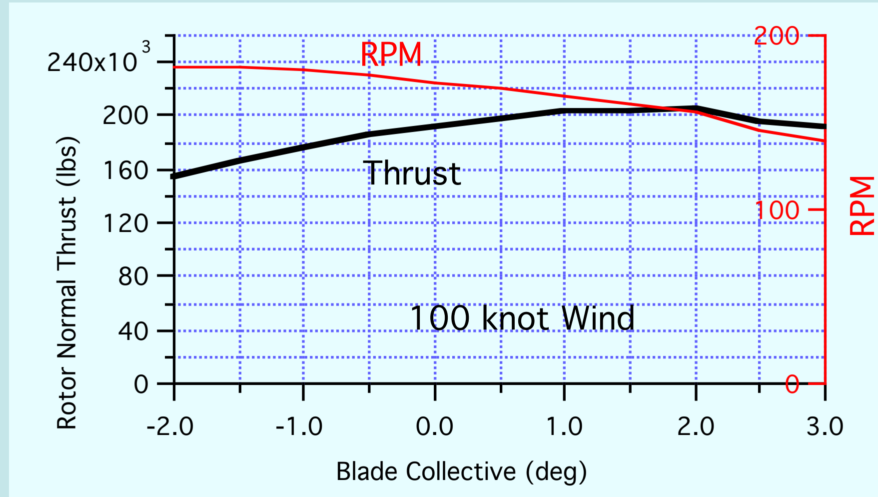
  - Sissingh sets the constant $K_{tip} = .93$

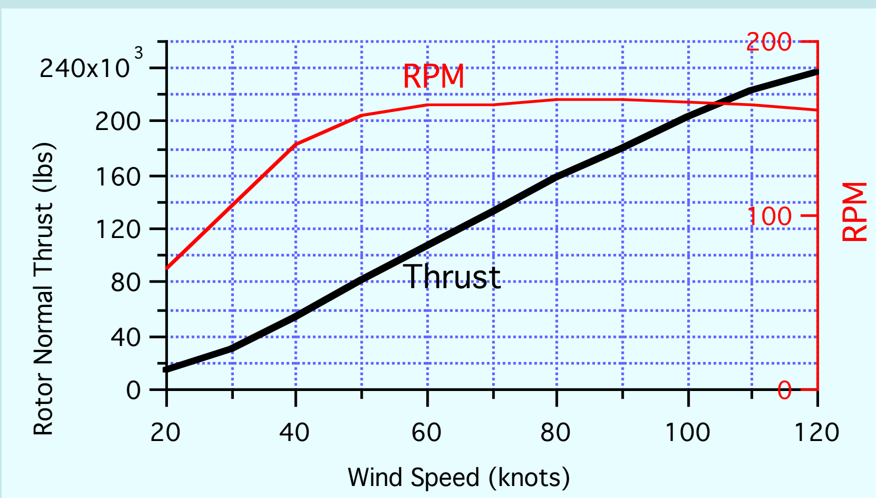
Example Rotor Characterizations

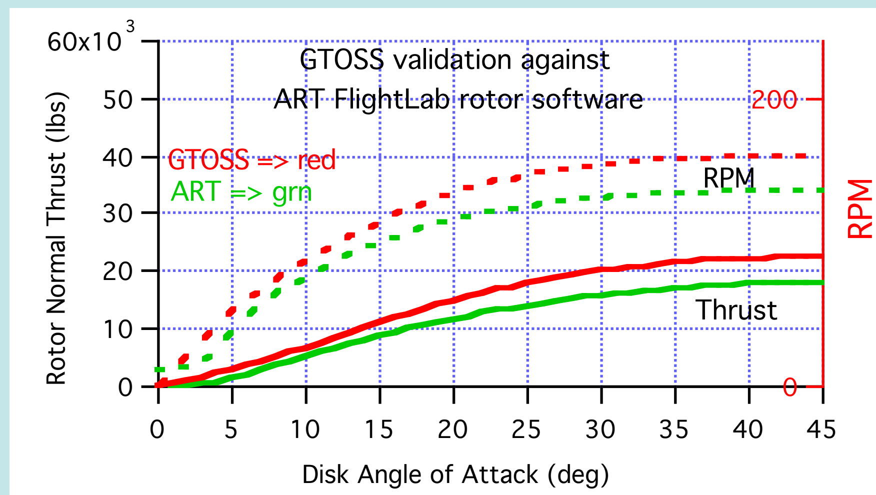
4 blade 100' dia rotor, NACA 0012 airfoil, 6' chord, no Twist

NOMINAL SETTINGS: 1 deg Collective, 100 kt Wind @ Sea level

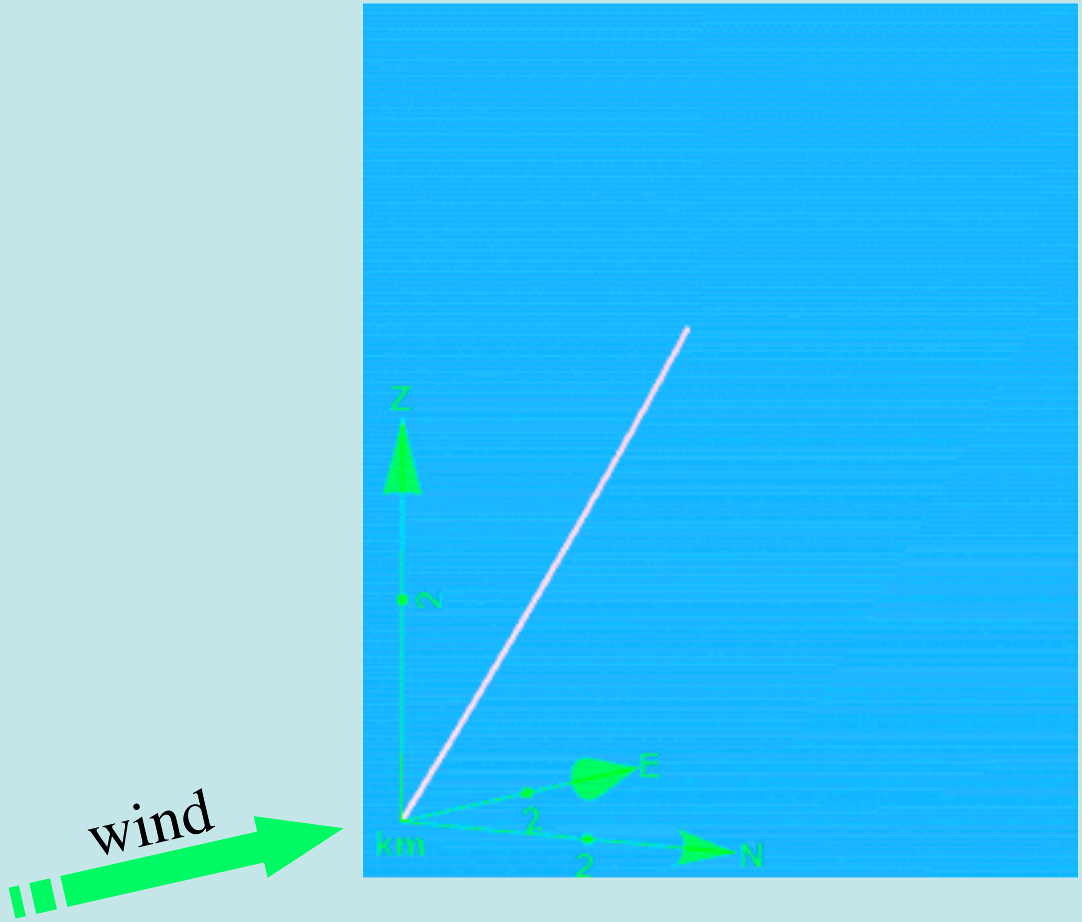








Movie of Typical Power Cycle

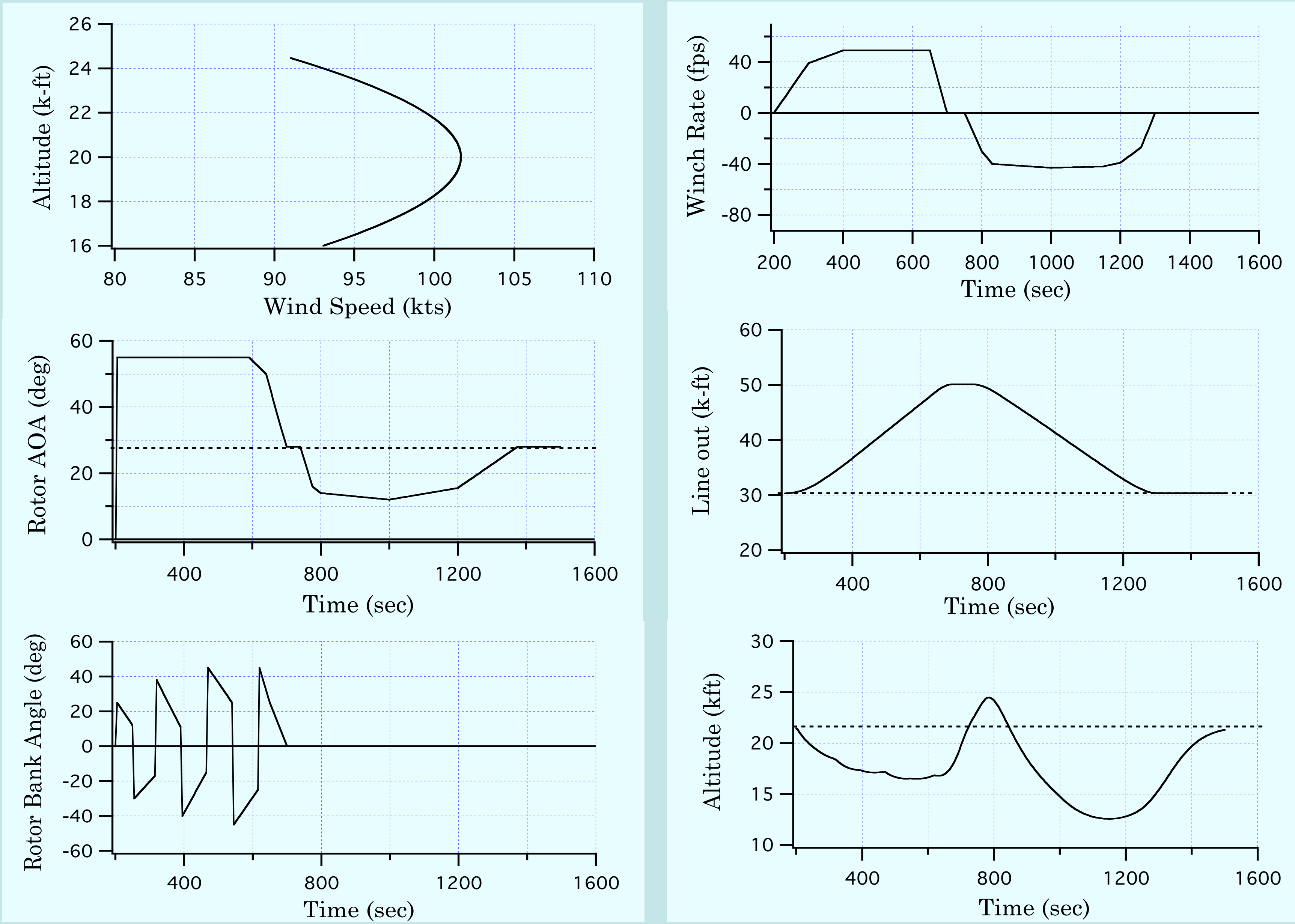


Tether Legend

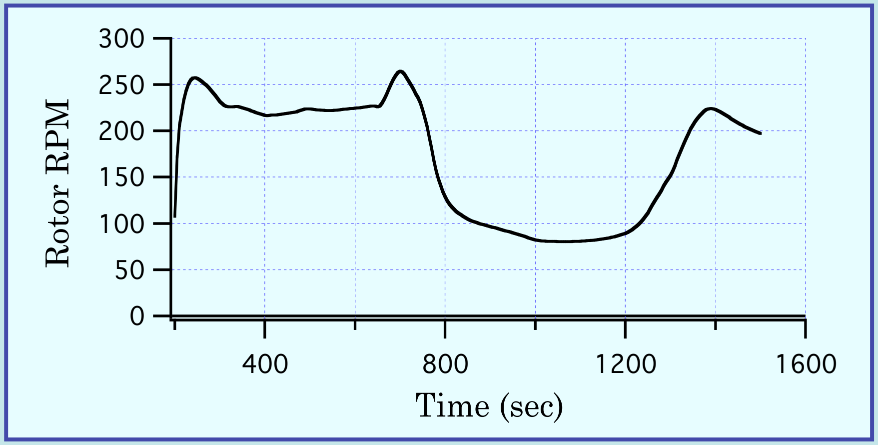
Red = Highest tension

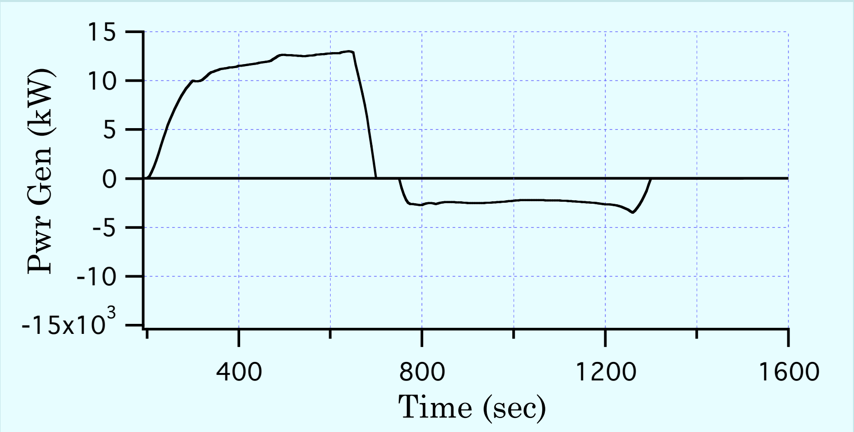
White = Lowest tension

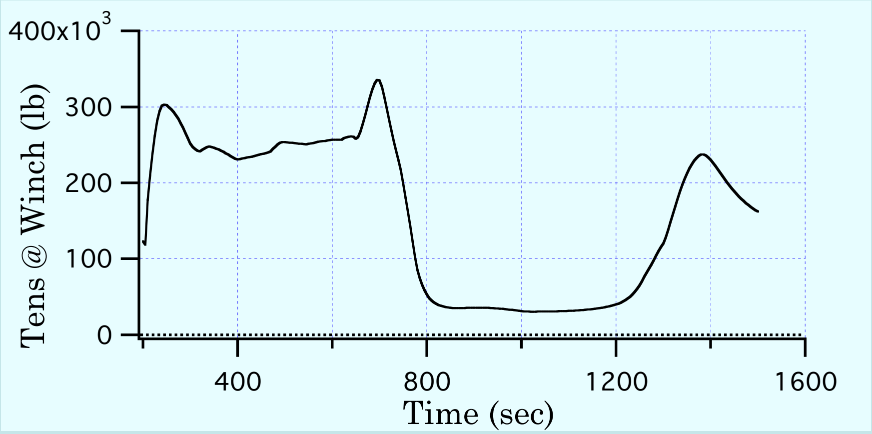
Example Trajectory Kinematics

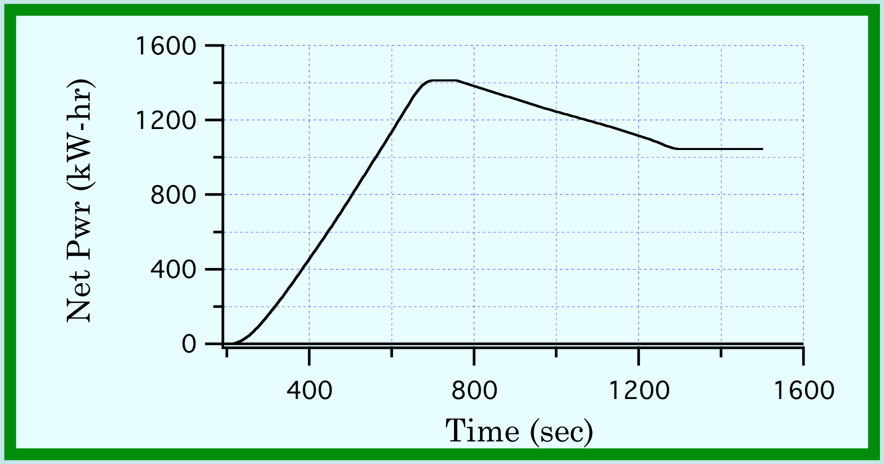


Example Trajectory Performance









Thanks for your Attention