Potential and Limits for Sweep- and Laminate-Induced Torsion Coupling

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Overview

- Introduction to Wetzel Engineering
- What is TBC?
- Why TBC?
- Where is TBC today?

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Wetzel Engineering

- In Business Since 2001
- Staff of 13
- Engineering Services for Wind Energy and Aviation

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Services

- Technology Assessment/Analysis
- Turbine/Blade Design/Optimization & Controls Engineering
- Full Blade Design
- Certification Support/Training & Loads Analysis
- Turbine Preliminary Design & Component Detail Design
- Forensics Analysis

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Blade Design Projects

Full Blade Designs Completed 2010-2011:

- *4 Utility Scale Blades (43.5, 45.3, 50.5, 56.3m)*
- *3 Small & Medium Sized Blades (4, 13, 26m)*

Full Blade Designs in Progress 2012

- *5 Utility Scale (51, 55, 58.5, 61, 100m)*
- *3 Medium Sized (14, 16, 21)*
- *Various pending*

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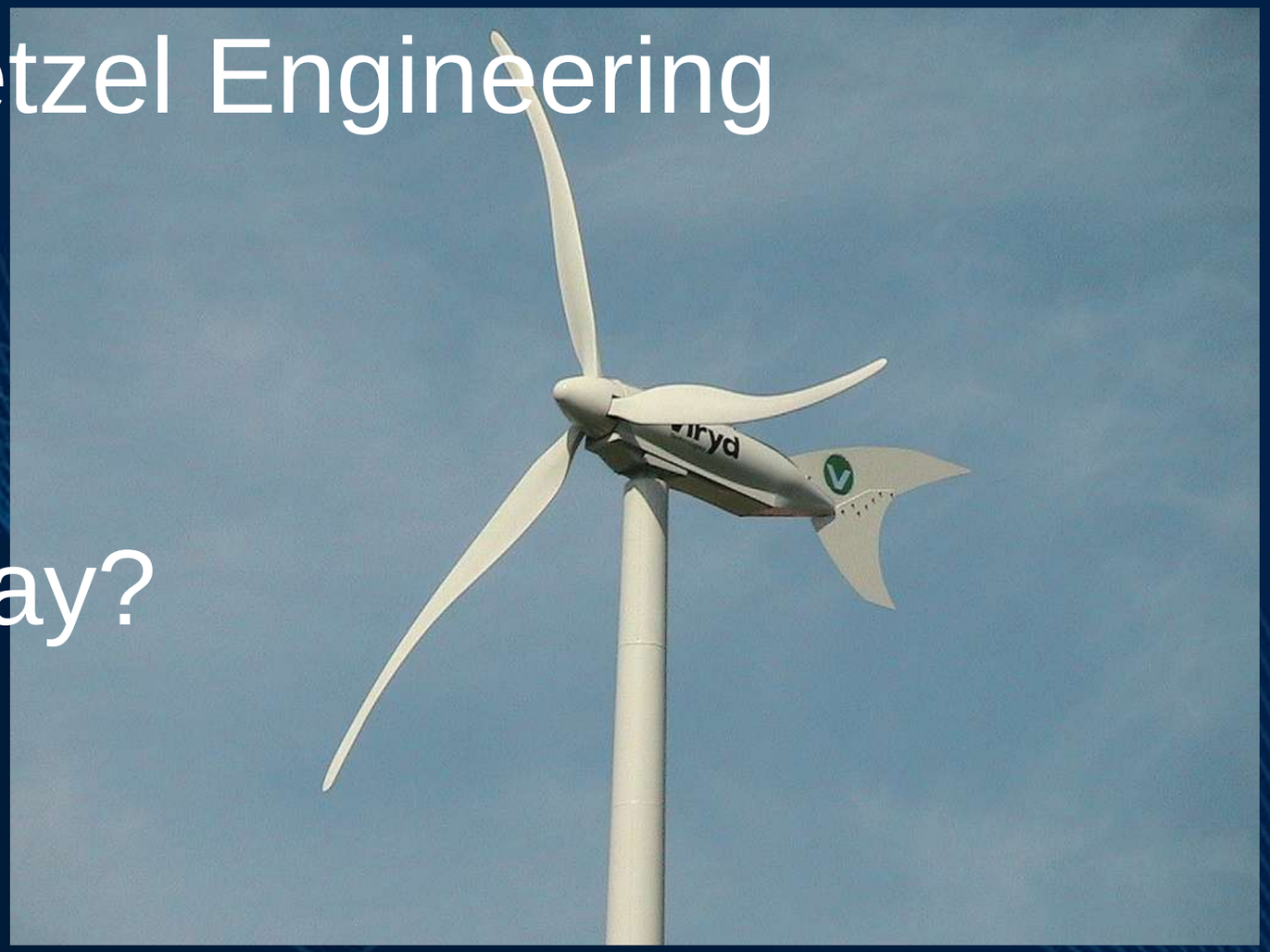

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What is Torsion-Bending Coupling?

- Coupling of Torsional Deformation (i.e., twist) to the Out-of-Plane Bending Deformation

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How to Achieve TBC?

- Geometric Coupling (Sweep)
  - Induces an external torque MZ
- Structural Coupling
  - Anisotropic Laminates
  - Structural Arrangement

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Geometric Coupling

- Sweep creates a torque arm
- Aero load on outboard sections induces torque load on inboard sections, inducing twist

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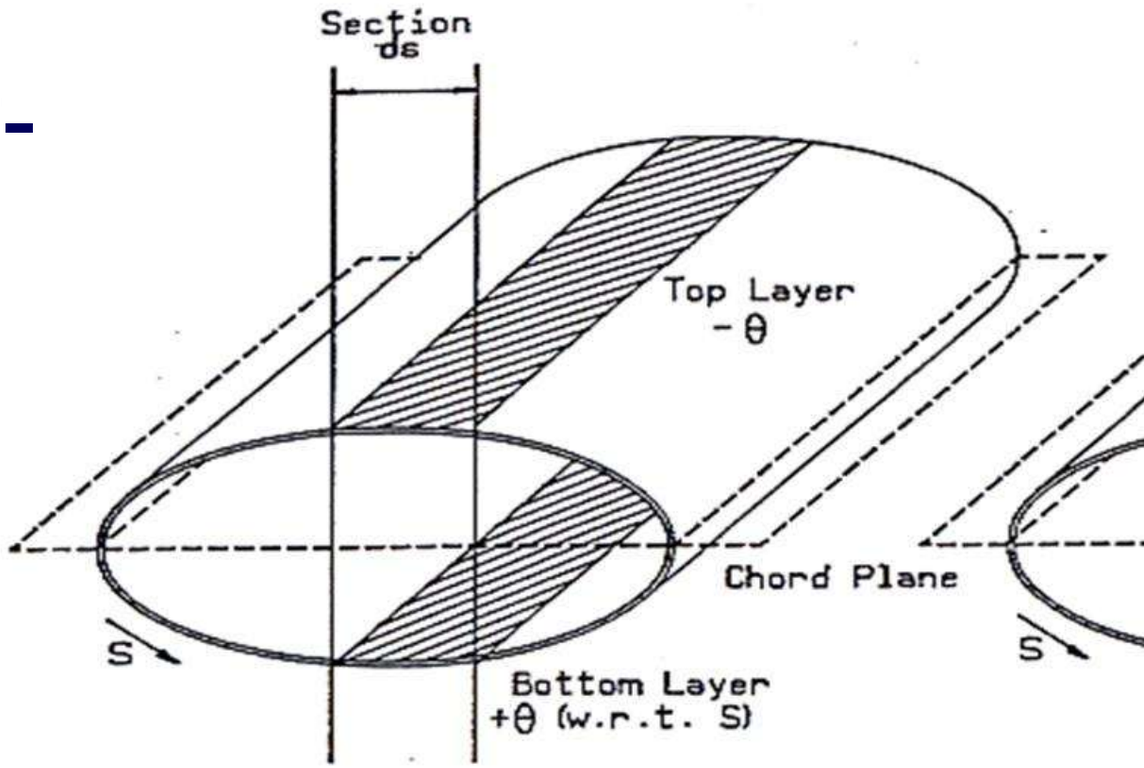
Anisotropic Laminates

- Unbalanced Off-Axis Carbon Induces a Shear-Tension Coupling
- Tension on PS and Compression on SS causes the shells to shear in opposite directions, inducing twist



(a) "Mirror" lay-up for bending/twisting coupling (θ changes sign below chord)

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Aeroelastic Tailoring

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Anisotropic Laminates

- Ideal off-axis angle for maximum coupling is ~20 degrees
- Limiting factor is in-plane shear stress in the laminate
  - This severely limits the potential for use in the spar caps – angles of no more than 8°
  - Risk associated with off-axis fibers in the spar caps is high

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Anisotropic Laminates

- Fabric with off-axis carbon can be fabricated using stitch-bonding
  - Angles of ~23° are achievable with common equipment
  - Angles of as low as 8° are achievable with available equipment – but very slow production
- Impact on manufacturing is negligible

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Anisotropic Laminates

- Off-axis carbon must be carefully reinforced with glass to strength against in-plane shear
  - Cost effective in the skin
  - Adds too much weight to the spar caps
- Recommended configuration is off-axis carbon in the skins

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Anisotropic Laminates

- Original: 20C/±45 G
  20C/+65G/-25G (±45G relative to 20C)
- GE Patent: 20C/-70G
- WEI Patent Pending: 25C/*X*G/*Y*G
  - Optimal Balance of Low Shear Stiffness and High Shear Strength

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Anisotropic Laminates

- WEI CG900
  - 500gsm carbon at 25 degrees
  - 400gsm E-glass reinforcement
  - R_{12}=133MPa
  - G_{12}=5.1GPa
  - R_{12}/G_{12} = 26,600μstrain

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Differences in the Methods

$$\begin{Bmatrix} \dfrac{d^2x}{dz^2} \\ \dfrac{d\phi_z}{dz} \end{Bmatrix} = \begin{bmatrix} \dfrac{1}{EI} & Q_{xz} \\ Q_{xz} & \dfrac{1}{GJ} \end{bmatrix} \begin{Bmatrix} M_y \\ M_z \end{Bmatrix}$$

2x2 Compliance Matrix

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Differences in the Methods

$$\begin{Bmatrix} \dfrac{d^2x}{dz^2} \\ \dfrac{d\phi_z}{dz} \end{Bmatrix} = \begin{bmatrix} \dfrac{1}{EI} & 0 \\ 0 & \dfrac{1}{GJ} \end{bmatrix} \begin{Bmatrix} M_y \\ M_z \end{Bmatrix}$$

For Sweep, Mz is a function of My

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Differences in the Methods

$$\begin{Bmatrix} \dfrac{d^2x}{dz^2} \\ \dfrac{d\phi_z}{dz} \end{Bmatrix} = \begin{bmatrix} \dfrac{1}{EI} & Q_{xz} \\ Q_{xz} & \dfrac{1}{GJ} \end{bmatrix} \begin{Bmatrix} M_y \\ 0 \end{Bmatrix}$$

For Laminate-Induced TBC There is no Significant MZ

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Comparison

- Laminate-Induced TBC
  - No External Torque Load
  - Enables Coupling in Blades with Normal Profiles
  - Requires custom fabrics that can be more expensive
  - Requires use of carbon in the shell

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Comparison

- Sweep
  - No custom fabrics
  - Does not require the use of carbon
  - Complicates fabrication of the girder and probably requires the use of prepreg for the girder
  - Induces external torque load that can be transferred through to the pitch system
  - More complicated tooling
  - Larger blade envelope affects transportation

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Recommendation

- Off-axis Carbon in Skin + Small Sweep
- Off-axis carbon in the skin only will not generally reach the shear strength limits of the material
- Small amounts of sweep can be used to reach the limit of the material strength
- Twist of 8-12 degrees at the tip is achievable
- Best combined with Independent Pitch Control

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Torsion-Bending Coupling

- Tailored torsion-bending coupling can be used to shed transient loads

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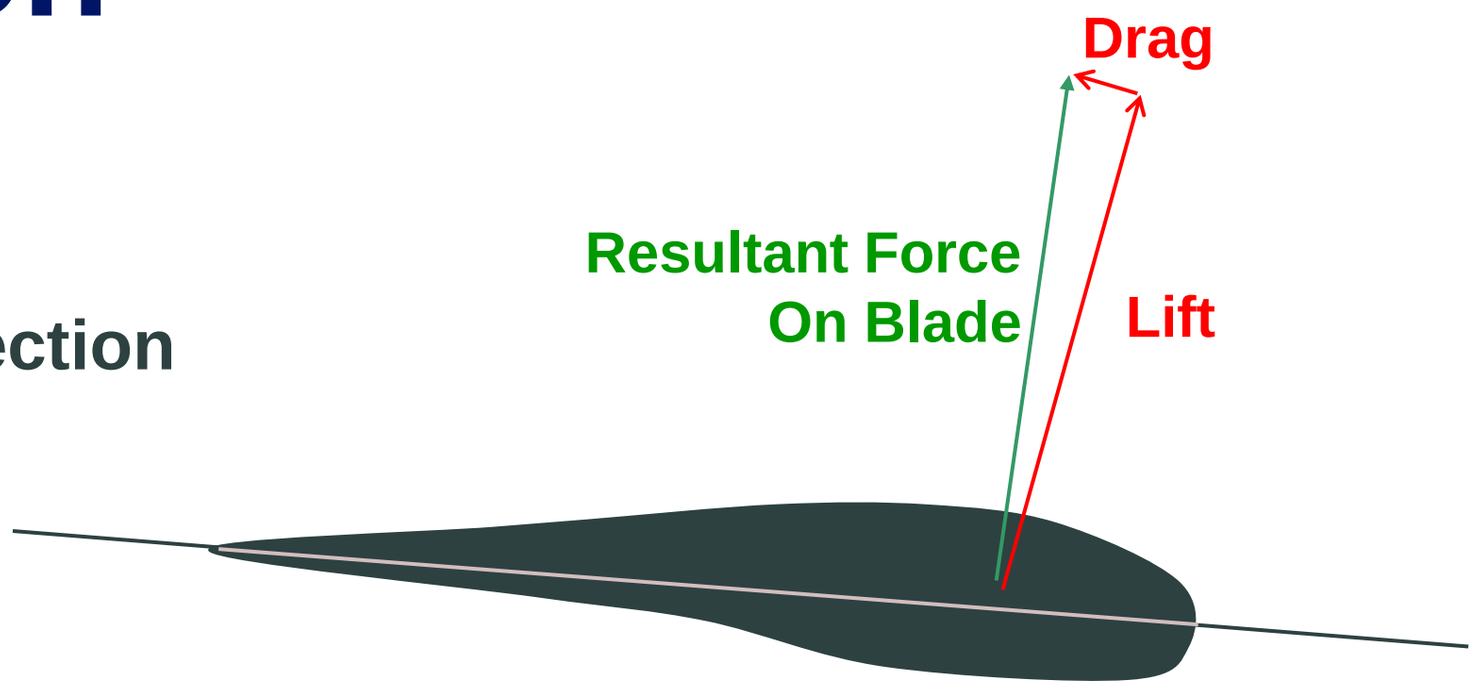
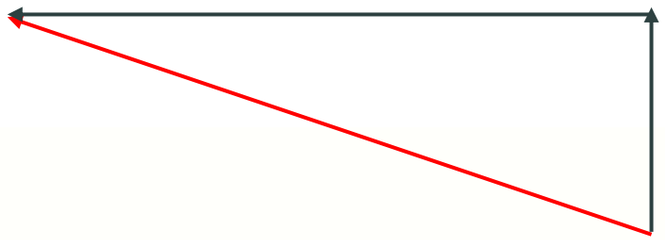
Normal Operation

Typical
Outboard Section





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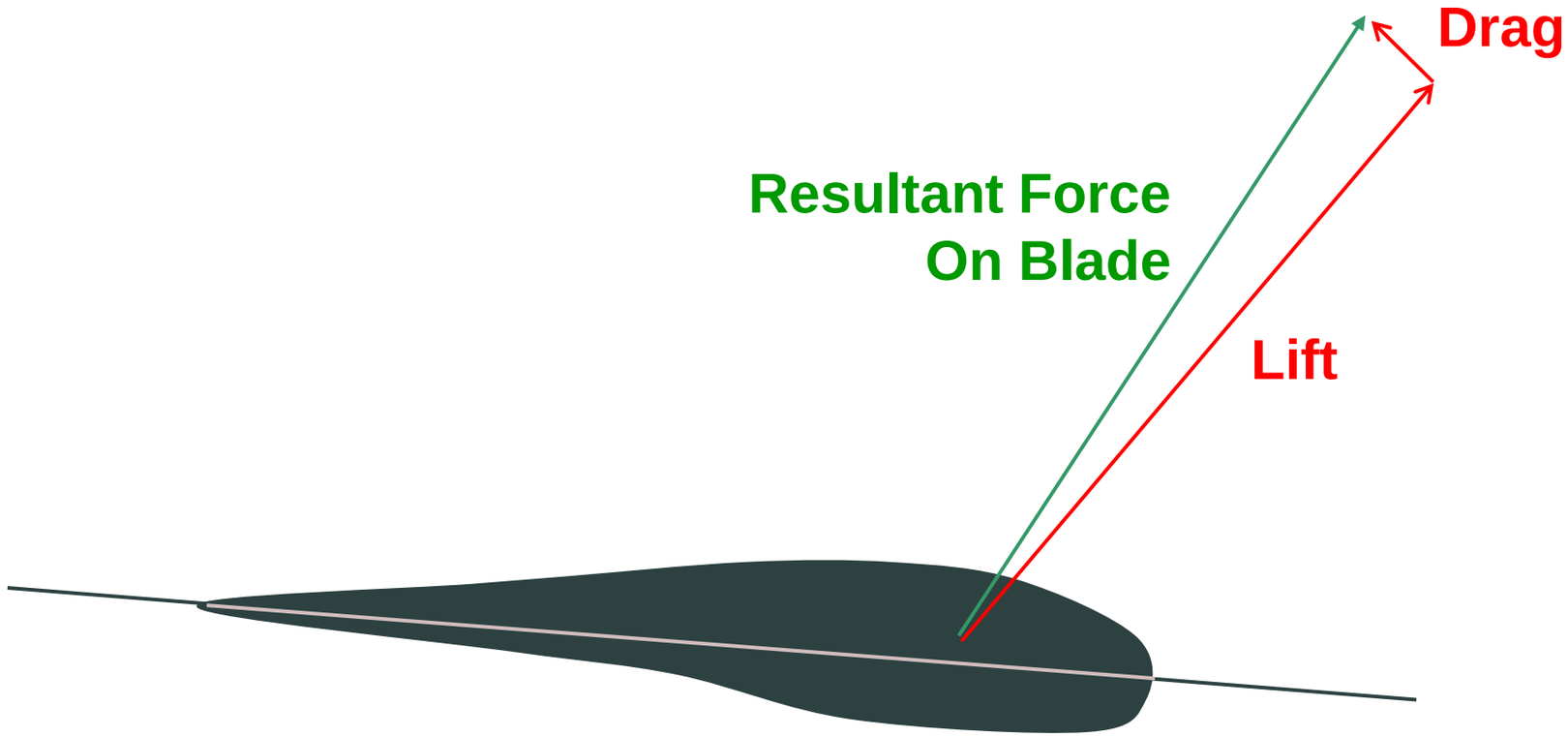
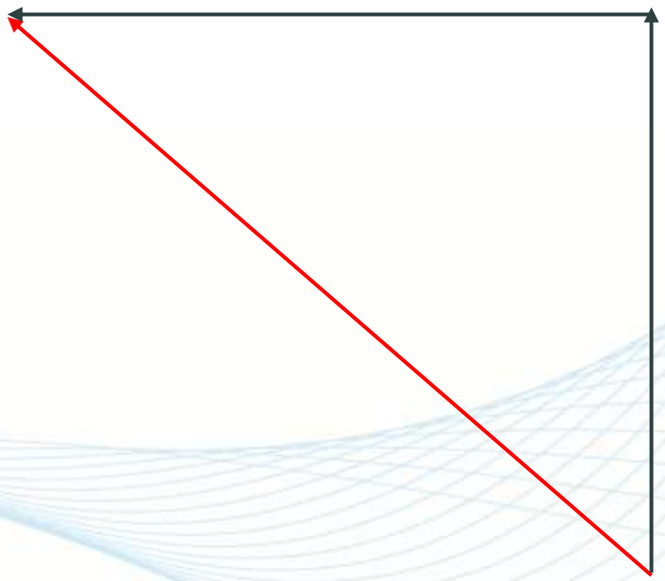
High-Speed Gust





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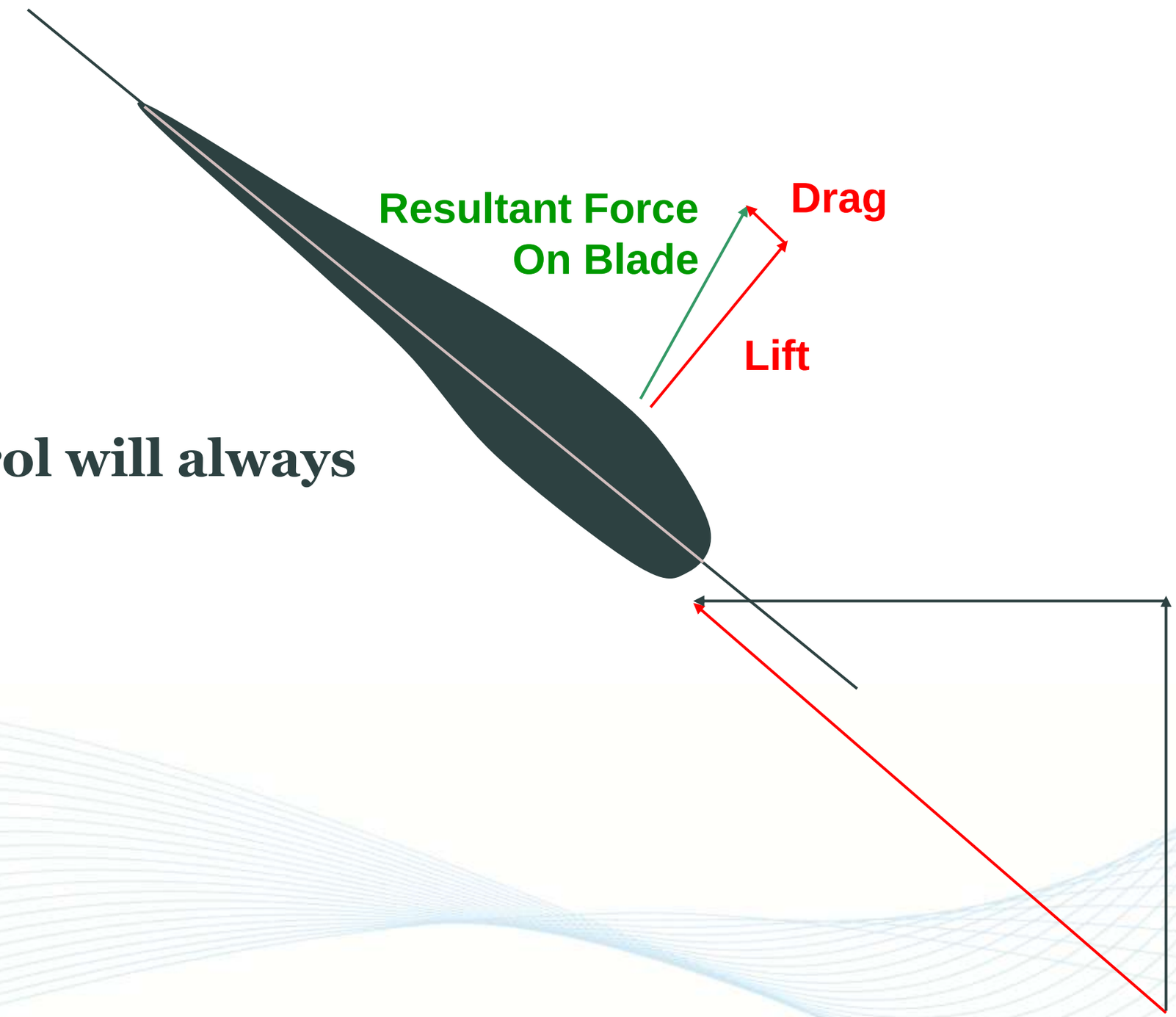
High-Speed Gust: Pitch



- **Active Pitch Control will always experience lag**

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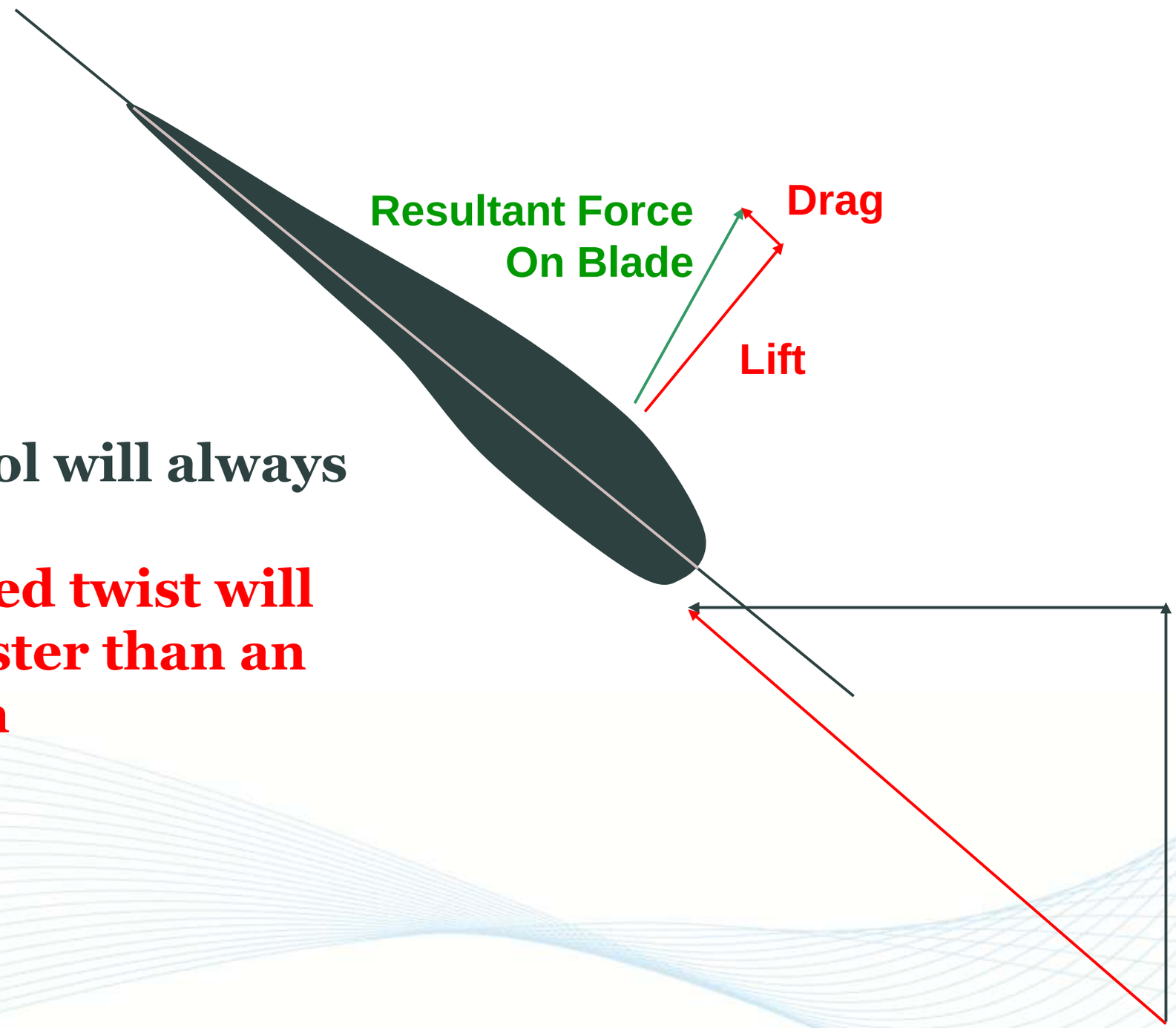
High-Speed Gust: TBC



- Active Pitch Control will always experience lag
- Passive flap-induced twist will always respond faster than an active pitch system

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Torsion-Bending Coupling

- Tailored twist-flap coupling can be used to shed transient loads
- Allows an increase in rotor diameter without increasing loads above baseline levels
- Increased Energy Capture
- Value of increased energy capture exceeds cost of implementing coupling
- ~8% Reduction in the cost of energy

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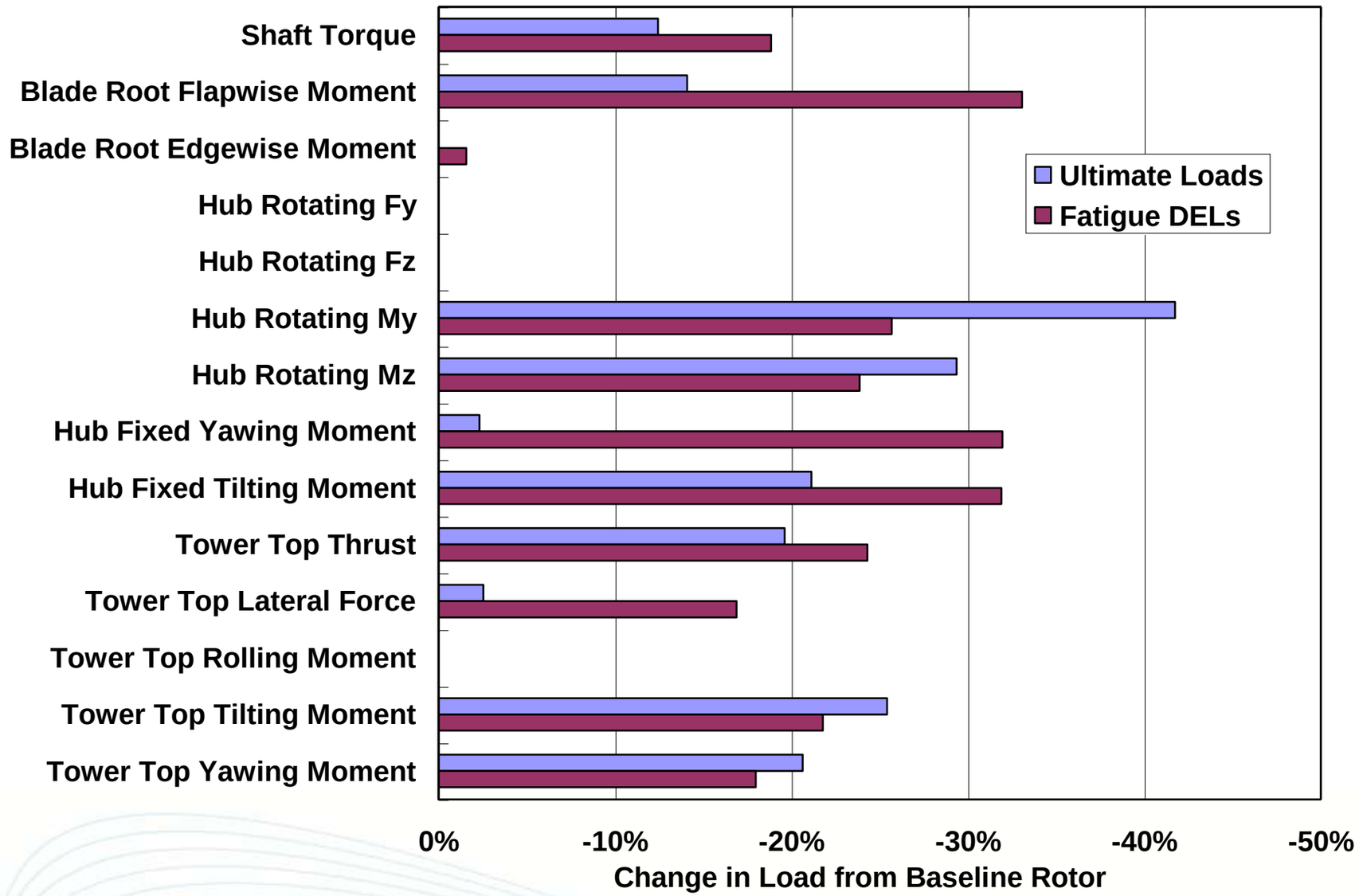
TBC: Potential Loads Reduction



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Industry Adoption

- No Blades in Commercial Production use Sweep or Laminate-Induced TBC
- Experimental Blades
  - GE 54m Swept
  - Knight & Carver Star Blade
  - Siemens Swept Blade
  - TX-100 9m TBC Blade
  - Viryd 4m Swept Blade
  - Wetzel 3.2m TBC Blade

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Industry Adoption

- Anticipated Commercialization
  - GE Sweep?
  - Siemens Sweep?
  - 100m TBC China 2014
  - 61m TBC + Sweep

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Thank you!

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