SAND2013-4114C

Impact of Modeling Approach on Flutter Predictions for Very Large Wind Turbine Blade Designs

Brian Owens, Todd Griffith, and Brian Resor
Sandia National Laboratories

John Hurtado
Texas A&M University

American Helicopter Society 69th Annual Forum
23 May, 2013
Phoenix, AZ

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Sandia National Laboratories

Outline

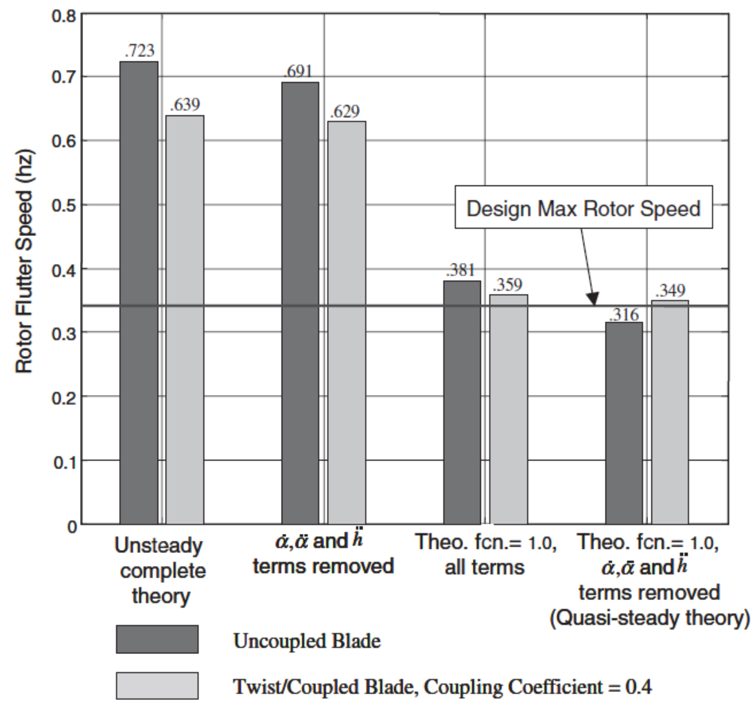
- **Introduction**
- **Previous Work**
- **Motivation**
- **Overview of BLade Aeroelastic Stability Tool**
  - Analysis Capabilities
  - Formulation
  - Analysis Procedures
  - Integration with SNL NuMAD
- **Demonstration**
- **Aeroelastic Representations**
- **Conclusions & Future Work**

Introduction

- **Flutter**
  - Dynamic aeroelastic instability
  - *Self-starting, potentially destructive vibration where aerodynamic forces couple with a structure's natural modes producing large-amplitude, diverging periodic motion.*
- **Consideration in aircraft design**
  - *Variety of flight conditions*
- **Wind Turbine Blades**
  - *Classical flutter*
  - *Stall induced flutter*
- **May be a consideration for larger, softer blade designs**

Previous Work

- **Lobitz, 2004**
  - Classical flutter
    - more catastrophic instability
    - coupling of torsional and flapwise modes
  - Concern for pitch regulated turbines
  - Isolated blade analysis
  - Preliminary blade design tool
  - Unsteady aerodynamic airfoil theory
  - Examined effects of flap-twist coupling
- **Hansen, 2007**
  - Stall induced flutter
  - Concern for stall-regulated turbines
  - Considers entire turbine system
  - Interaction of inflow with turbine vibration
  - Typically mediated with structural damping



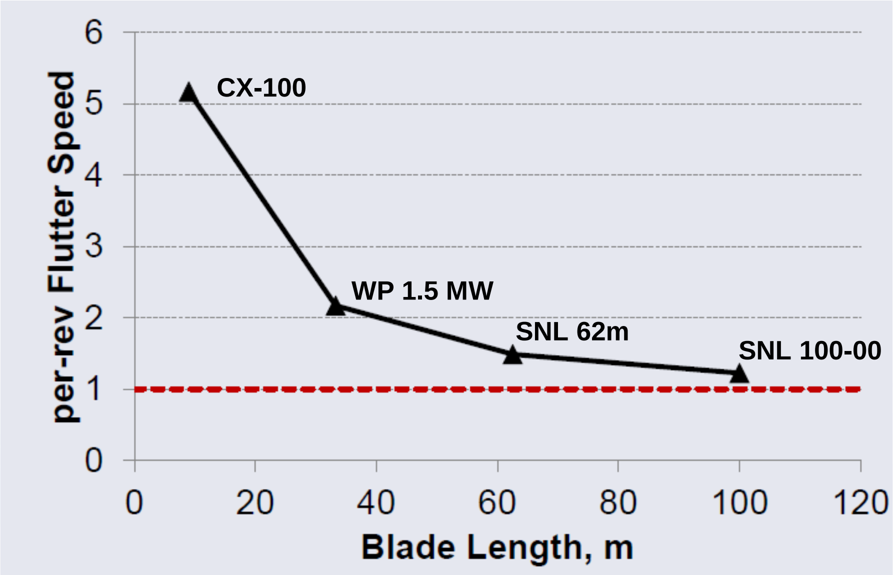
Lobitz, D.W. *Wind Energy*, 2004

SNL Legacy Flutter Tool

- **Originally developed for VAWTs**
  - Adopted and modified for HAWT blades
  - Some remnants of VAWT specific assumptions
    - Averaged or uniform aerodynamic properties
    - Less accurate geometric representation of HAWT blades
- **Heavy use of NASTRAN's DMAP capability**
  - NASTRAN for basic structural dynamics formulation
  - Pre-stress effects
  - DMAP for aerodynamic effects
  - Made use of complex eigensolver
  - Licensing and computing overheads
- **User intensive, manual procedure**

Motivation

- **Traditionally not a concern for utility scale blades**
- **Trends of decreasing flutter margin with blade size**

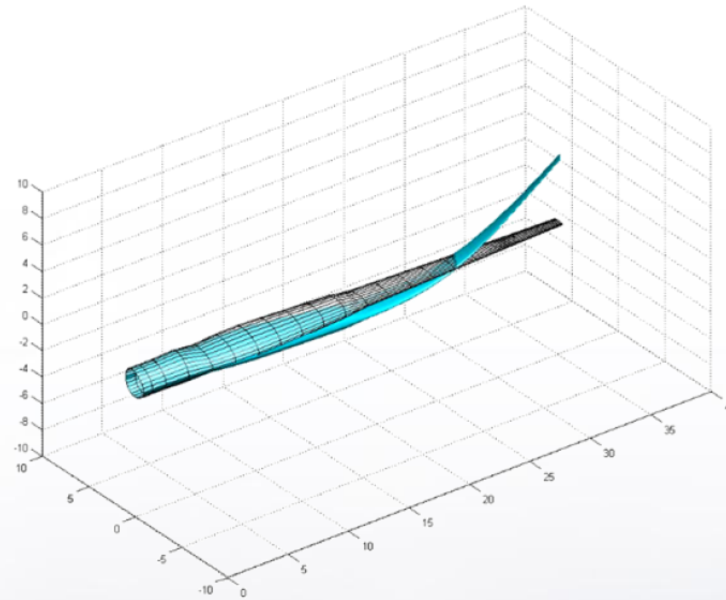


- **Critical look of existing tools**
  - Modeling approaches
- **Development of improved design tool solutions**

BLAST: Analysis Capabilities

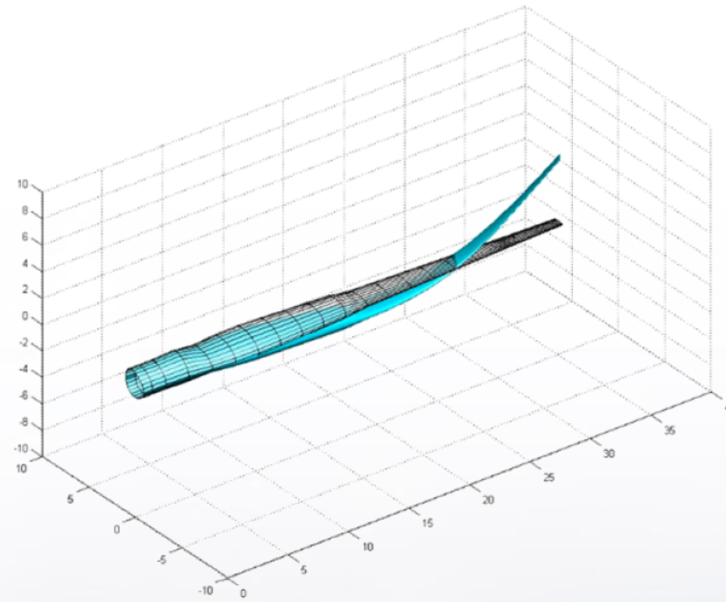
BLade Aeroelastic Stability Tool

- **Classical flutter**
  - Rotating blade
  - Parked blade
  - Divergence of rotating blade
- **Better geometric representation**
  - Swept blades
  - Offset mass axes
  - Coupling factors for composite materials
  - Better representation of mass and stiffness distributions, concentrated terms



BLAST: Analysis Capabilities (2)

- **Gyroscopic effects**
  - Coriolis
  - Spin Softening
- **Stress stiffening effects**
- **License-free, in-house finite element code**
- **Integrates with existing tools**
  - NREL FAST file format
  - NuMAD interface
- **Automation**
- **Visualization**



Sandia National Laboratories

BLAST: Formulation Structural Dynamics

- **Three-dimensional Euler-Bernoulli Beam Element**
- **Hamilton's principle**

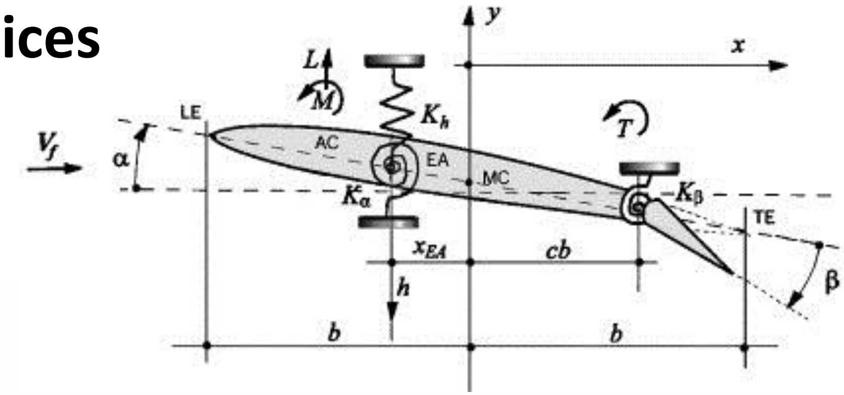
$$\delta \int_V \left(\mathscr{T}(q,\dot{q}) - \mathscr{V}(q)\right) dV = \delta \mathscr{W}_{np}$$

- **Kinetic Energy**
  - Fundamental structural motion
  - Rotor speed
  - Offset mass axes
- **Strain Energy**
  - Coupling factors for composites
- **Finite Element Formulation**

$$\boxed{M\ddot{x} + (C + \boldsymbol{G(\Omega)})\dot{x} + (K(x) - \boldsymbol{S(\Omega)})x = \boldsymbol{F_C(\Omega)}}$$

BLAST: Formulation
Unsteady Aerodynamics

- **Unsteady effects due to shed vortices**
- **2D airfoil theory**
  - Zero-yaw conditions
  - Flow in mid-span to tip regions



- **Theodorsen Function**
  - Complex valued $C(k), k = \dfrac{\omega b}{V}$

$$L = \pi\rho b^2\left[\ddot{w} + V\dot{\theta} - ba\ddot{\theta}\right] + 2\pi\rho V b C(k)\left[\dot{w} + V\theta + b\left(\frac{1}{2} - a\right)\right]$$

- **Non-potential force in Hamilton's principle**

$$M = \pi\rho b^2\left[ba\ddot{w} - Vb\left(\frac{1}{2} - a\right)\dot{\theta} - b^2\left(\frac{1}{8} + a^2\right)\ddot{\theta}\right] + 2\pi\rho V b^2\left(a + \frac{1}{2}\right)C(k)\left[\dot{w} + V\theta + b\left(\frac{1}{2} - a\right)\right]$$

$$\boxed{(M + \boldsymbol{M_A(\Omega)})\ddot{x} + (G(\Omega) + \boldsymbol{C_A(\Omega,\omega)})\dot{x} + (K(x) - S(\Omega) + \boldsymbol{K_A(\Omega,\omega)})x = 0}$$

BLAST: Analysis Procedure

1. Select an operating condition (rotor speed)
2. Obtain a static equilibrium solution

$$K(x_{eq}) - S(\Omega))x_{eq} = F_C(\Omega)$$

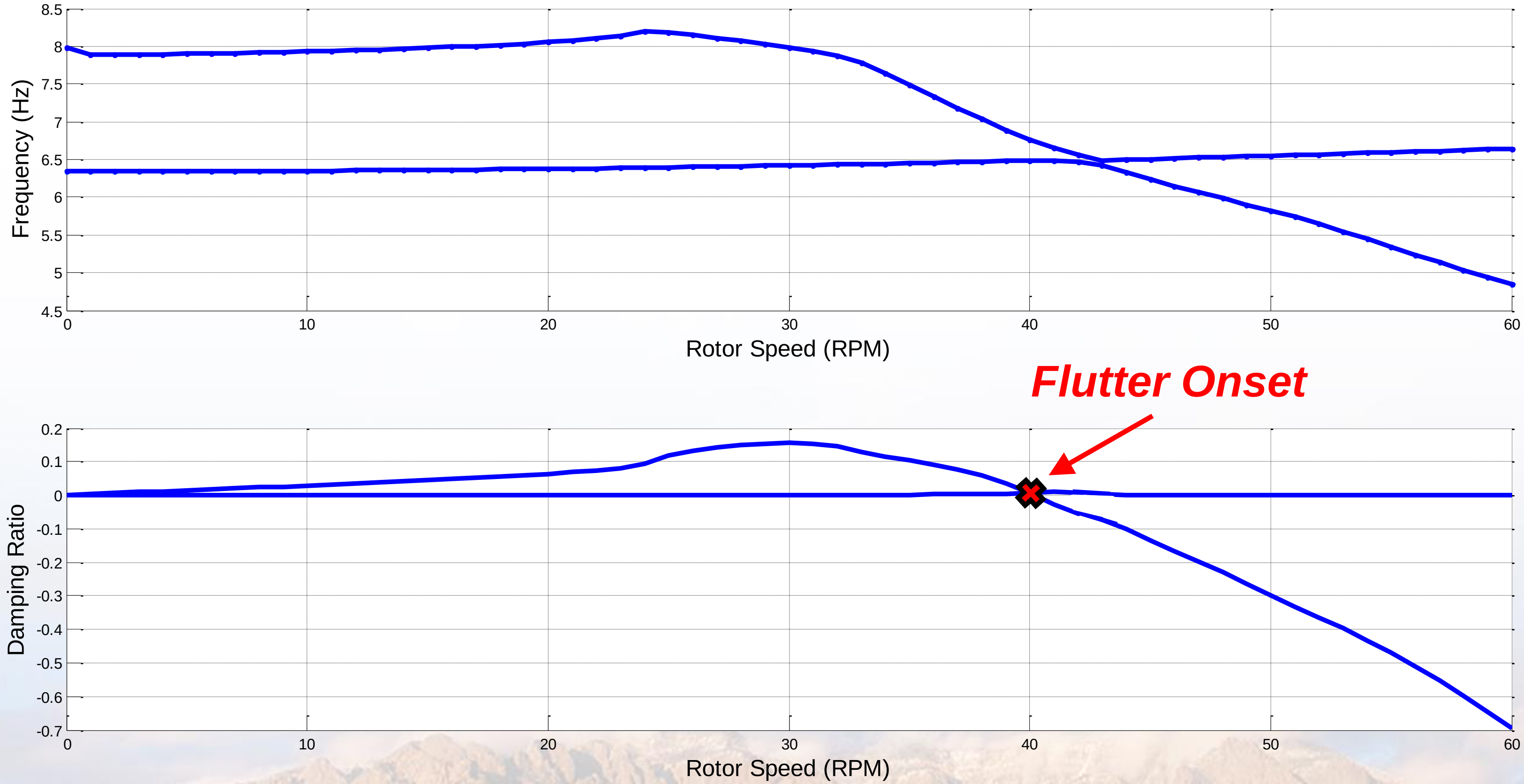
3. Provide an initial guess for mode frequency

$$(M + M_A(\Omega))\ddot{x} + (G(\Omega) + C_A(\Omega, \boldsymbol{\omega}))\dot{x} + (K(x_{eq}) - S(\Omega) + K_A(\Omega, \boldsymbol{\omega}))x = 0$$

4. Perform modal analysis
5. Select mode of interest
6. Update frequency, iterate until converged
7. Repeat for other modes
8. Continue to next operating condition

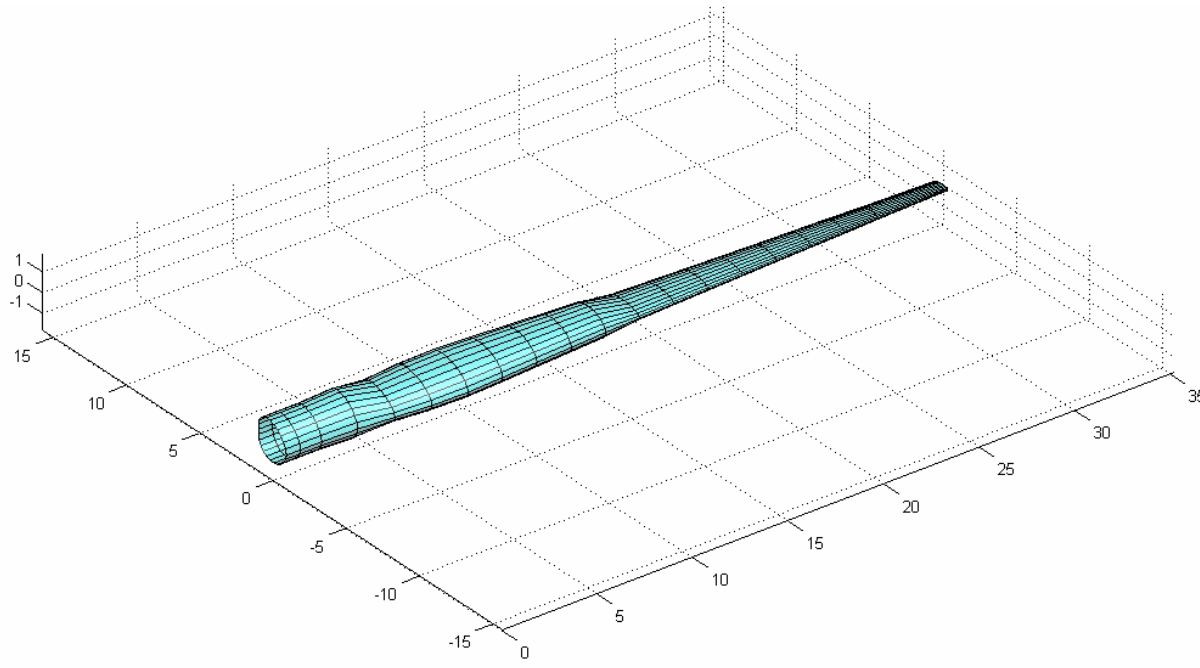
Automated & Efficient

Frequency & Damping vs. Rotor Speed

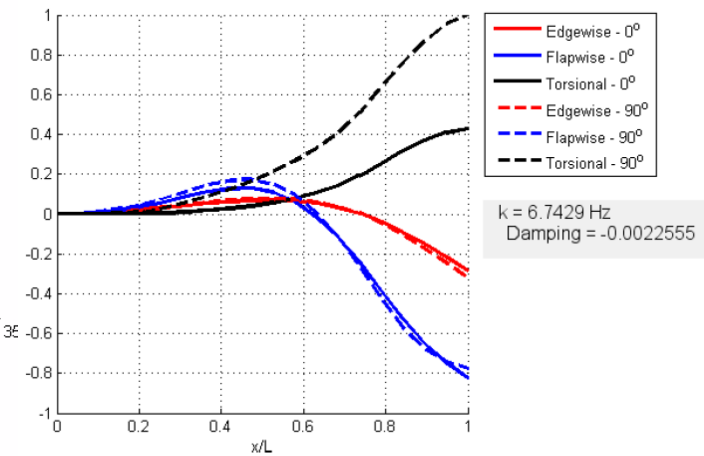


Mode Shape Visualization

3D Animation:

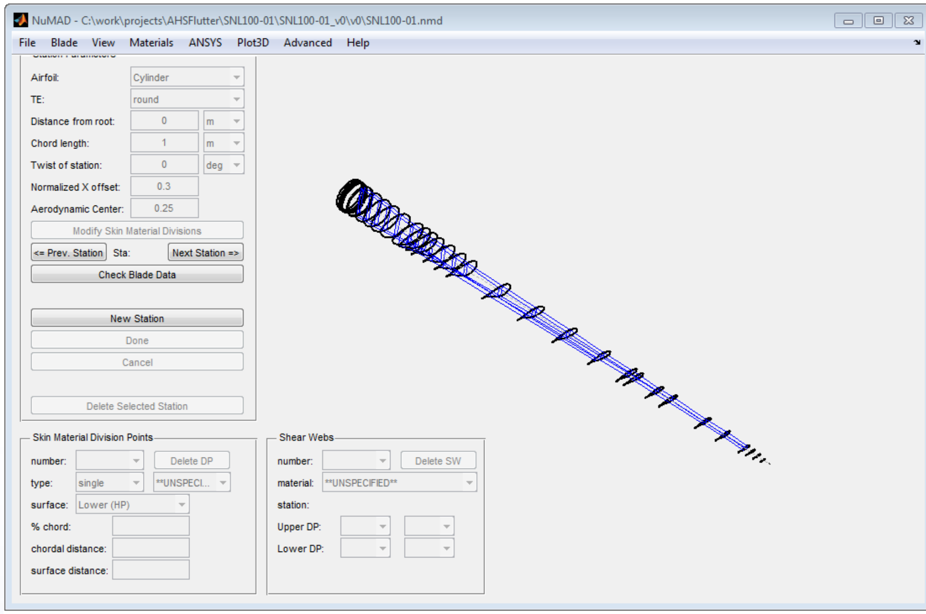


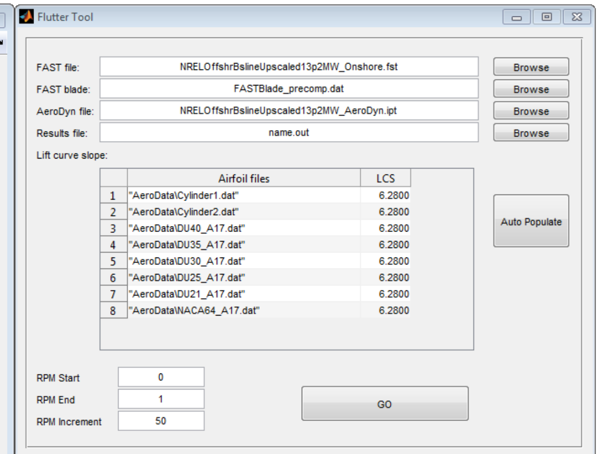
Flexural Axis Deformation:

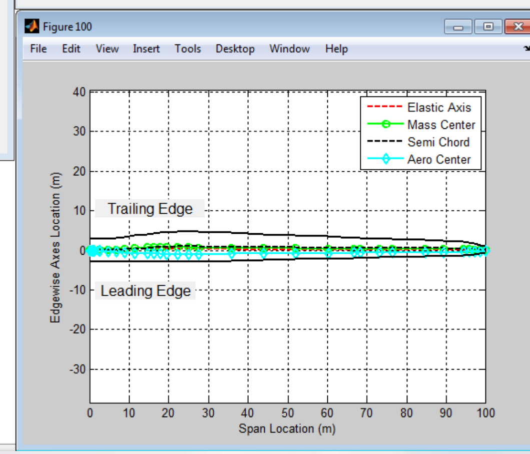


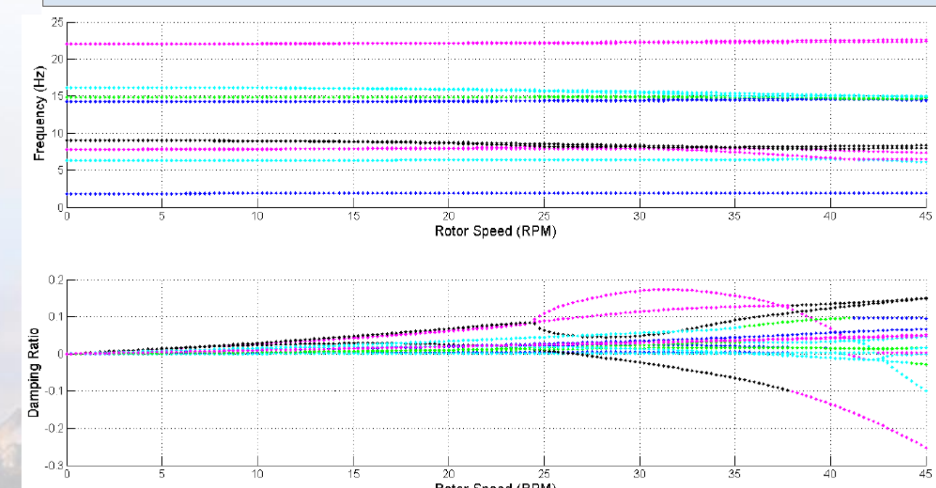
Sandia National Laboratories

Integration with NuMAD





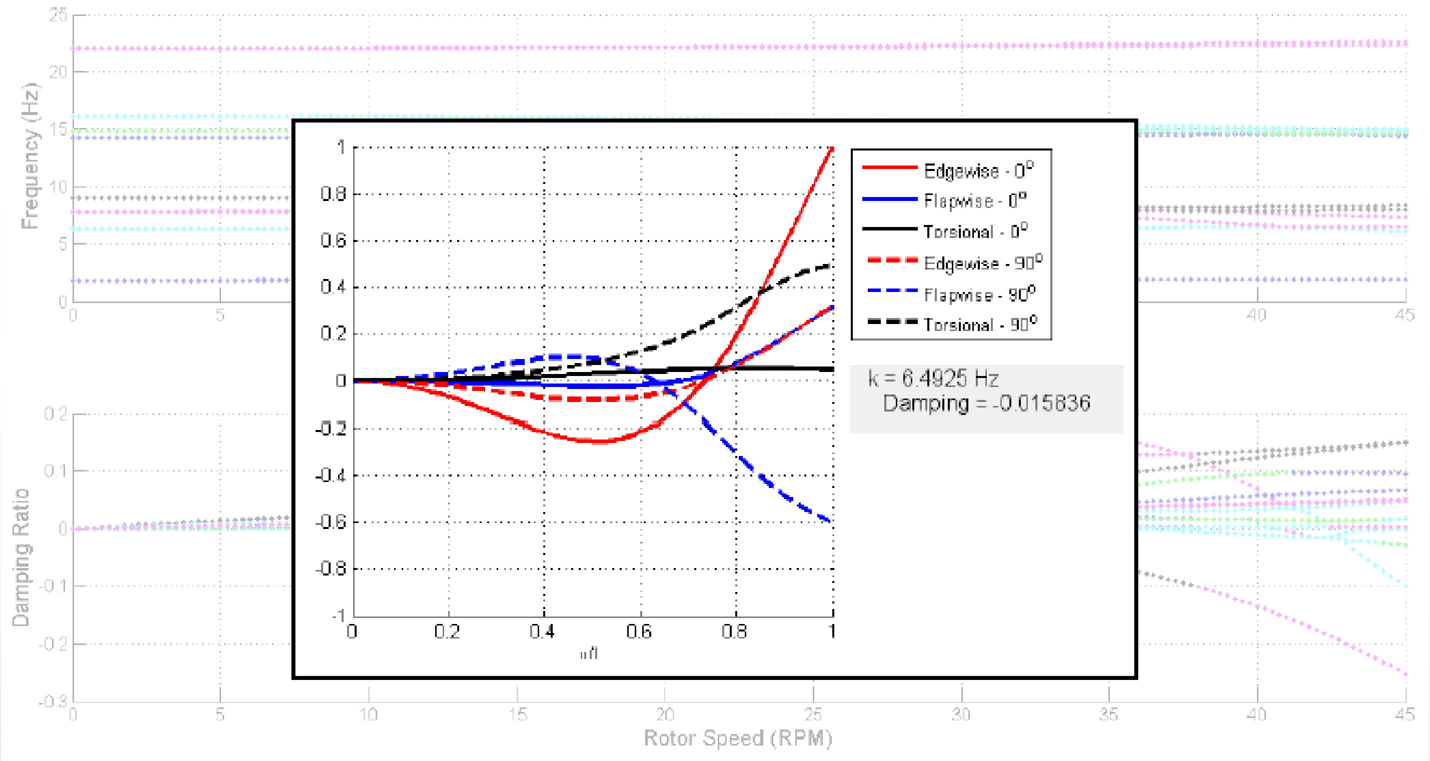




Sandia National Laboratories

WindPACT 1.5MW Blade

- **33 meter, utility scale**



Potential Flutter Speeds:

"Softer" trends, higher system modes:

26.6 RPM (1.33)

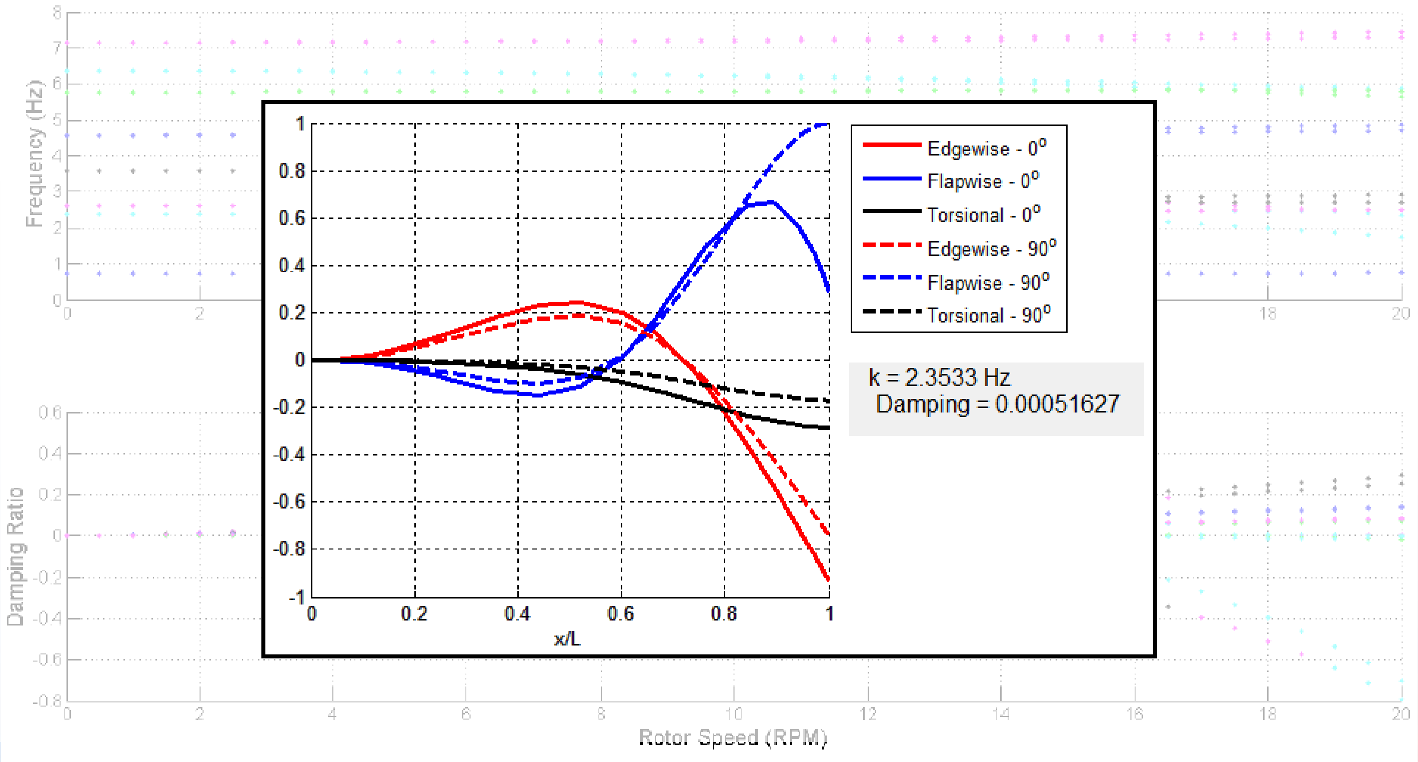
36.1 RPM (1.81)

"Harder" trend, lower system mode:

42.3 RPM (2.12)

SNL100-00 Blade

- 100 meter, very large blade



Potential Flutter Speeds:

"Softer" trends, higher system mode:
9.68 RPM (1.30)

"Harder" trend, lower system mode
14.40 RPM (1.94)

Studying Complex Representations

- **Conventional structural dynamics system**
  - M is real, but C and K may be complex (aerodynamics)

$$M\ddot{x} + C\dot{x} + Kx = 0$$

- **Employ modal analysis to decouple system**

$$\Lambda = \Phi^T M \Phi \qquad x = \Phi\eta$$

- **Assume off diagonal components are zero**

$$\Lambda\ddot{\eta} + \hat{C}\dot{\eta} + \hat{K}\eta = 0$$

$$\eta = a\exp(\lambda t)$$

$$\dot{\eta} = a\lambda\exp(\lambda t) = \lambda\eta$$

$$\ddot{\eta} = a\lambda^2\exp(\lambda t) = \lambda^2\eta$$

- **Characteristic Equation for Uncoupled, Complex System**

$$\hat{C} = c + i\tilde{c} \qquad \widehat{K} = k + i\tilde{k}$$

$$\left\{\Lambda\lambda^2 + (c + i\,\tilde{c})\lambda + \left(k + i\,\tilde{k}\right)\right\}\eta = 0$$

Studying Complex Representations

- **Eigenvalues**

$$\lambda = -\frac{c + i\,\tilde{c}}{2\Lambda} \pm \sqrt{\frac{(c^2 - \tilde{c}^2)}{4\Lambda^2} + i\frac{c\tilde{c}}{2\Lambda^2} - \frac{(k + \tilde{k})}{\Lambda}}$$

$$A = \frac{(c^2 - \tilde{c}^2)}{4\Lambda^2} - \frac{k}{\Lambda} \qquad \sqrt{A + iB} = a + i\,b$$

$$B = \frac{c\tilde{c}}{2\Lambda^2} - \frac{\tilde{k}}{\Lambda}$$

- **No Complex Conjugate Pairs!**

$$\lambda = \left(-\frac{c}{2\Lambda} \pm a\right) + i\left(-\frac{\tilde{c}}{2\Lambda} \pm b\right)$$

No Damping: $\lambda_1 = -\lambda_2 = a + i\,b$

- **Extracting physical information**
  - Real valued 2nd order system: $\ddot{x} + 2\xi\,\omega_n\dot{x} + \omega_n^2 x = 0$
  - Not applicable to complex representations! $\lambda_{1,2} = -\xi\,\omega_n \pm i\,\omega_n\sqrt{1 - \xi^2}$

Sandia National Laboratories

Real Valued Representation

- **Real valued systems are preferable**
  - No ambiguity in physical meaning of eigenvalues/vectors
  - Use of conventional structural dynamics analysis methods
  - Insight from structural dynamics experience

- **Aeroelastic Representations**

$$L_{circ}(\theta,\dot{\theta}) = 2\pi\rho U_\infty bC(k)\left[U_\infty\theta + b\left(\frac{1}{2}-a\right)\dot{\theta}\right]$$

$$L_{circ}(\theta,\dot{\theta}) = L_\theta\theta + L_{\dot{\theta}}\dot{\theta}$$

Complex valued:

$$L_\theta = 2\pi\rho U_\infty^2 bC(k)$$

$$L_{\dot{\theta}} = 2\pi\rho U_\infty C(k)b^2\left(\frac{1}{2}-a\right)$$

- *C(k) is complex*
- *Complex system*
- *Employ complex eigensolver*
- *Ambiguity in physical meaning*

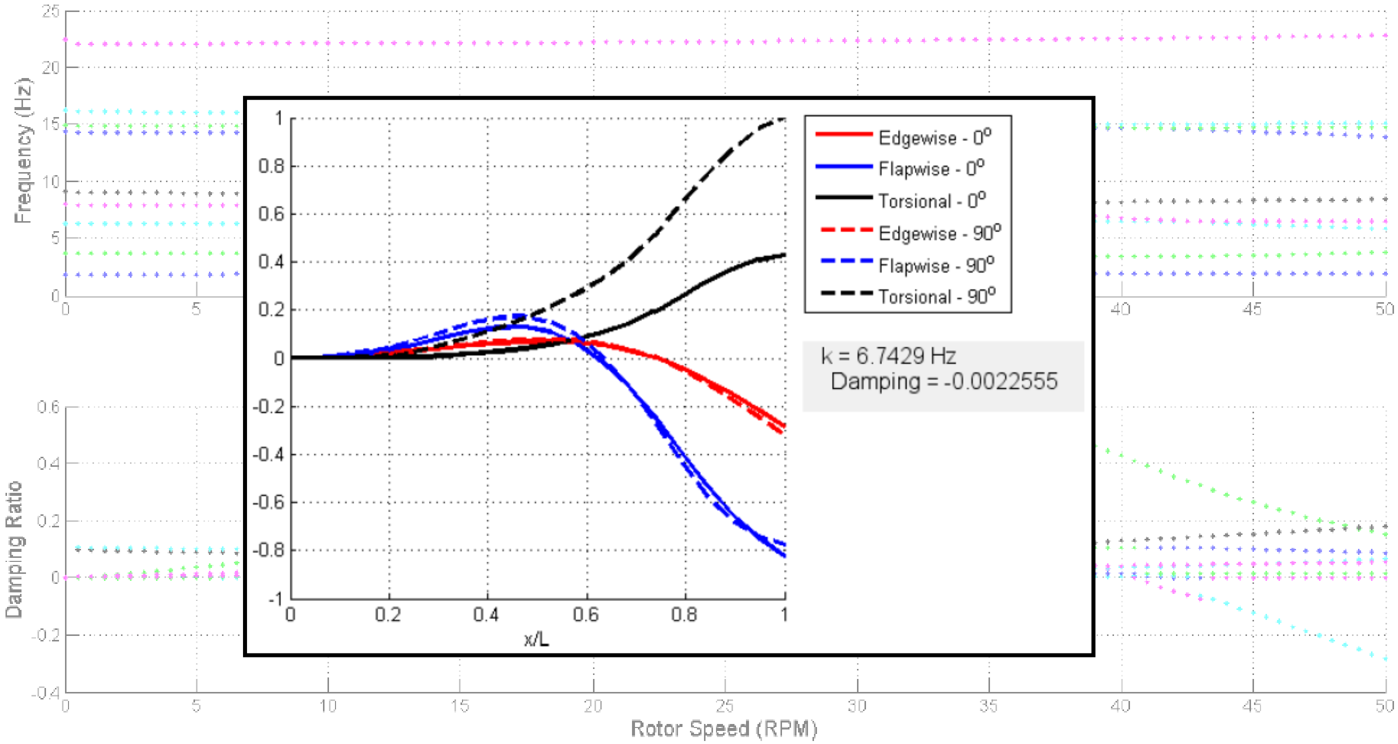
Real valued:

$$L_\theta = 2\pi\rho U_\infty^2 b\left[F(k) - G(k)b\left(\frac{1}{2}-a\right)\omega\right]$$

$$L_{\dot{\theta}} = 2\pi\rho U_\infty b\left[G(k)U_\infty + F(k)b\left(\frac{1}{2}-a\right)\right]$$

- *C(k) = F(k) + iG(k)*
- *Real system*
- *Conventional structural dynamics system*
- *Understood physical meaning*

Revised WindPACT 1.5MW



Flutter Speed:

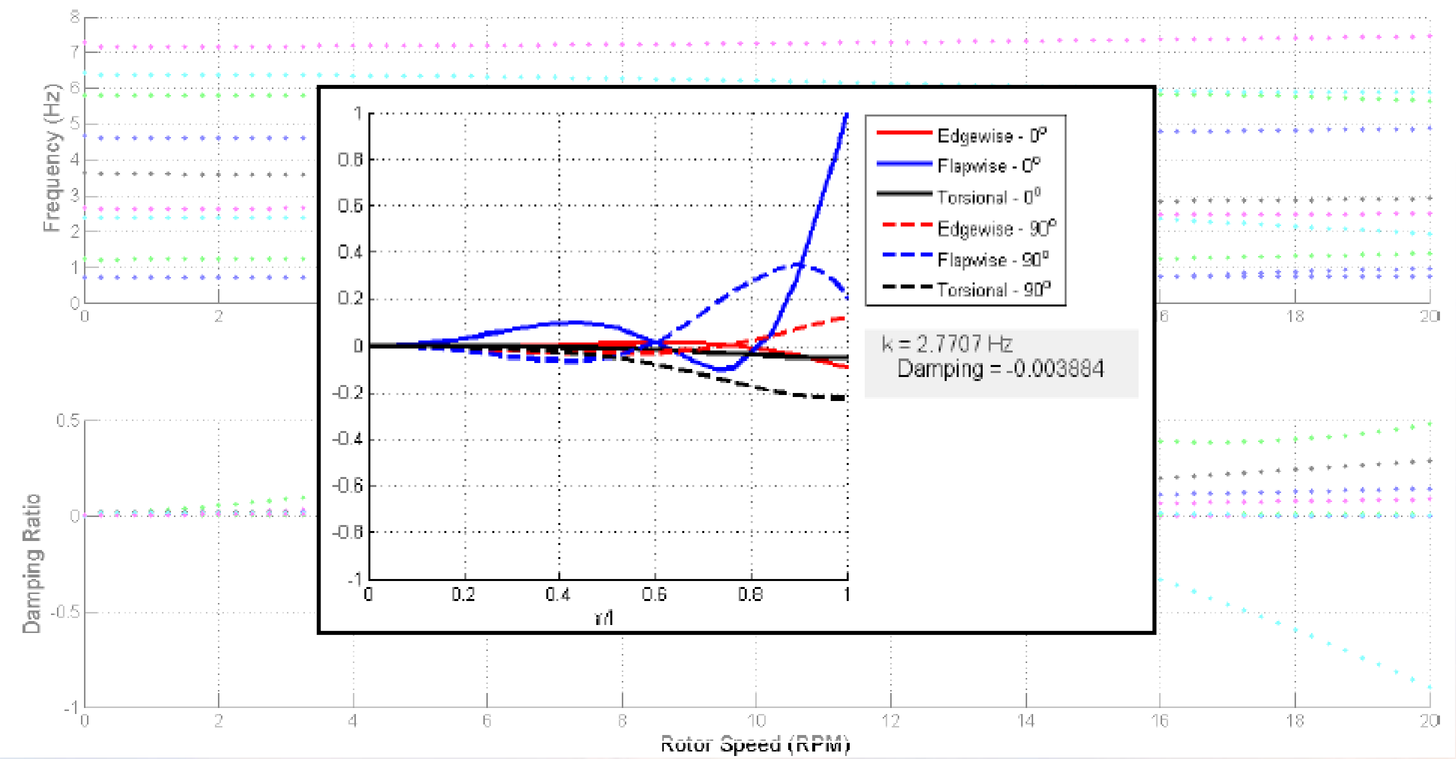
40.6 RPM (2.03)

Complex Rep:

42.3 RPM (2.12)
(4% difference)

Comparable estimates with legacy flutter tool.

Revised SNL100-00



Flutter Speed:

13.05 RPM (1.75)

Complex Rep:

14.4 RPM (1.94)
(10% difference)

Higher than initial estimates with legacy flutter tool

Conclusions

- **Custom, updated design tool for flutter of blades**
  - Better geometric representation of blades
  - Automated software, allows thorough analysis
  - License free & integrates with existing tools
  - Flexible for future research needs
- **Explored aeroelastic representations**
  - Real vs. complex
  - Adopted real valued representation
- **Revised flutter estimates for very large blades**
  - Increased flutter margins compared to estimates using the legacy flutter tool
  - Need a critical assessment of flutter in very large blades

Future Work

- **Validation of flutter prediction for a HAWT blade**
- **Comparison to higher fidelity approaches**
  - Understanding limitations of BLAST
  - Sufficiency for initial design estimates
- **Further enhancement of BLAST**
  - Extension from isolated blade to turbine analysis
  - Accounting for inflow
  - Other improvements as a result from validation and comparison efforts