The Rotorcraft Aerodynamics Library:

A Modelica Library for Simulation of Rotorcraft Aerodynamics and Whirl Flutter

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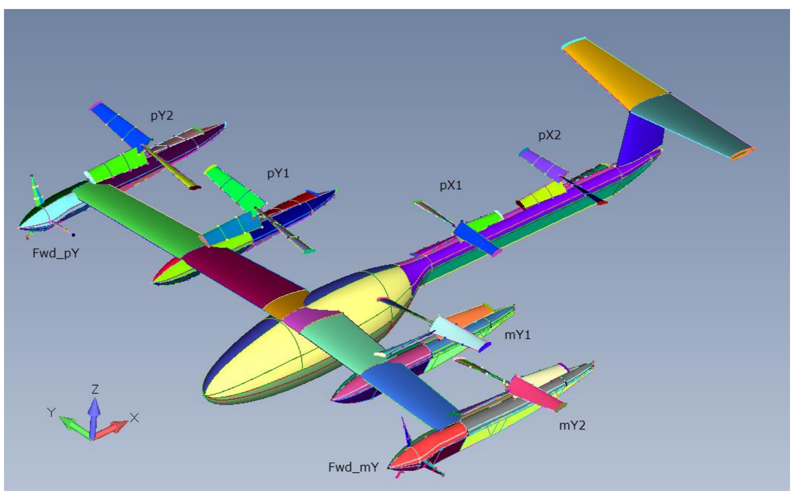
Increasing Need for Multidisciplinary Rotorcraft Modeling

- Emerging eVTOL (electric Vertical Take-Off and Landing) aircraft tightly couple many physical domains
  - Aerodynamics, rotor mechanics+dynamics, electrical motor dynamics, control system, power electronics, etc.
  - Many independent rotors for vertical lift and forward propulsion



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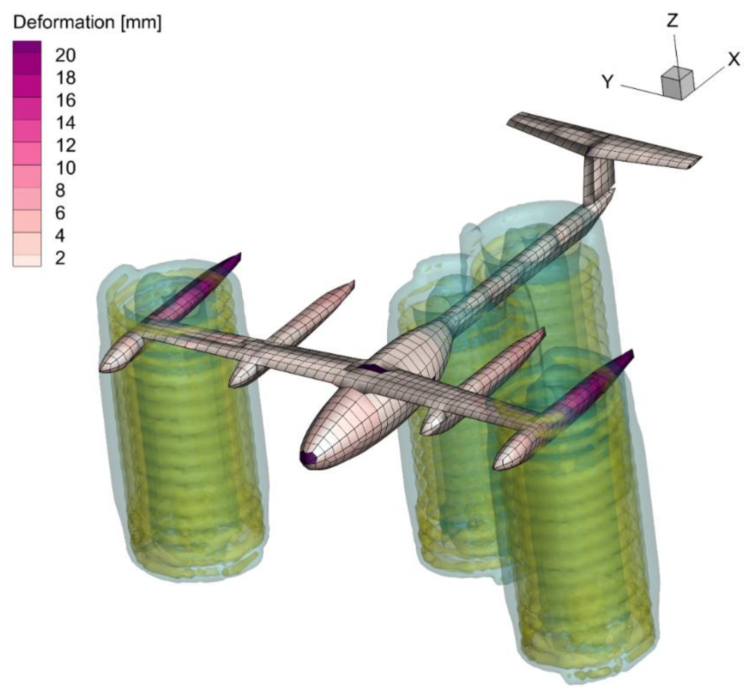
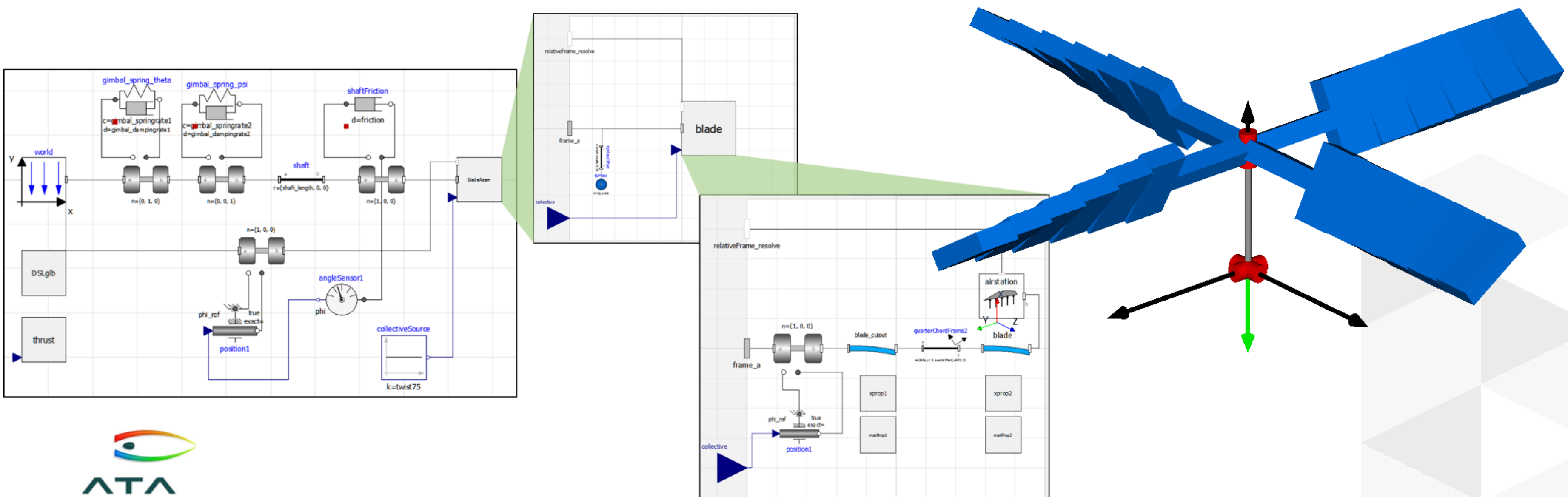


What Makes the eVTOL Problem Difficult?

- Multiple interacting rotor wakes
  - Traditional rotorcraft have few, widely spaced rotors
- Variable RPM rotors
  - Most rotorcraft are designed for a constant RPM
    - Many reasons: engine constraints/power optimization, avoiding structural modes, simplifying envelope calculations (e.g., whirl flutter)
- Electric rotors
  - Coupling with electric system requires power supply, thermal, and efficiency considerations
- Independent rotors
  - Under-constrained rotor trim problem (more rotors than trim objectives)
- Existing analysis tools are insufficient
  - Designed for aero-structural analysis of traditional rotorcraft (few rotors at fixed RPM)
  - Cannot analyze coupled electrical system or variable RPM

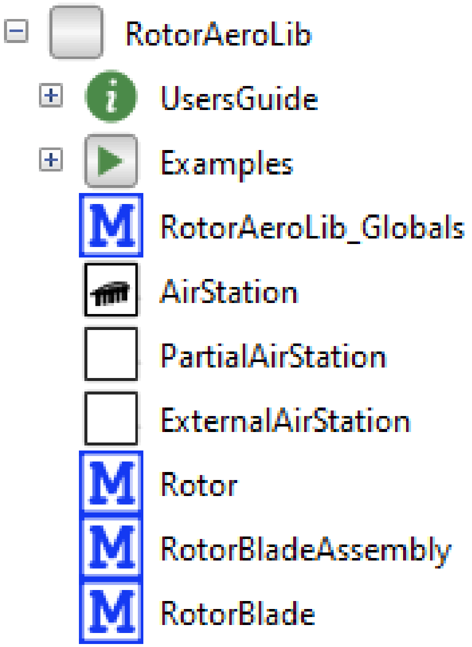
Modelica Enables Easy Coupling of the Various Physical Domains

- Many components can already be modeled/coupled with the MSL
  - Multibody dynamics and rotor mechanics
  - Unique mechanisms can be modeled
    - Various hub topologies and control mechanisms
  - Electric motors and electric power systems
  - Aircraft guidance and control system
- Aerodynamics need to be separately modeled and coupled to the blades



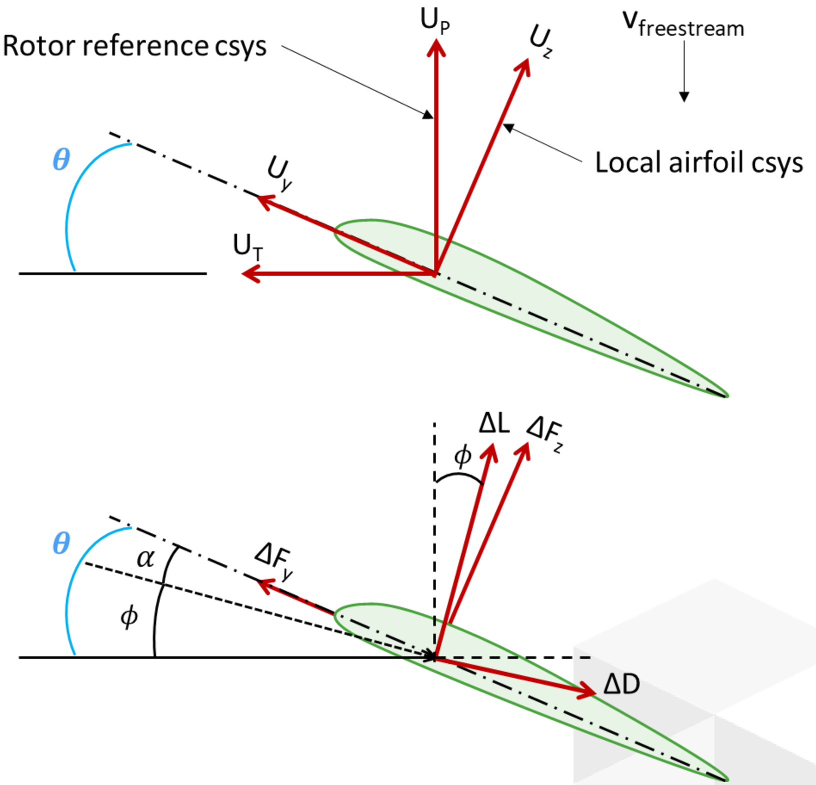
The Rotorcraft Aerodynamics Library (*RotorAeroLib*)

- Supports modeling rotor aerodynamics within a Modelica model
- Compliments the MultiBody library of the Modelica Standard Library
- Contains specialized modeling blocks for:
  - Modeling blade aerodynamics and transferring forces to blade
  - Modeling the rigid or flexible blade with twist and cross-sectional mechanical/aerodynamic properties
  - Assembling multiple blades into a rotor
  - Interfacing the blades with the rotor control system (i.e., swashplate and linkages)
- Makes use of open-source *DeployStructLib* Modelica library for rigid/flexible blades
- Usage examples included



Blade Aerodynamics Start with Blade Element Theory (BET)

- *RotorAeroLib.AirStation* model calculates the blade aerodynamic forces
  - An *AirStation* is attached in the airfoil coordinate system
  - Also connects to the rotor reference coordinate system to define geometric/collective angle
  - Multiple *AirStations* span the length of the blade to capture varying air flow speeds
    - Ultimately converging on the asymptotic limit
  - Lift coefficients defined as a quadratic function of α
  - Most of this merely sets up basic fluidic force calculations and projects the forces into the correct coordinate system



θ = *geometric/collective angle*
α = *angle of attack*
ϕ = *inflow angle*

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Advanced Options Implement Blade Element Momentum Theory (BEMT) and Other Corrections

- Global parameters in *RotorAeroLib. RotorAeroLib_Globals* enable advanced correction factors:

Inflow correction for BEMT:

$$\lambda^2 + \left(\frac{\sigma C_{l,\alpha}}{8} - \lambda_c\right)\lambda - \frac{\sigma C_{l,\alpha}}{8}\theta\tilde{r} = 0$$

$$U_P = V_r + \lambda V_{tip}$$

Aspect ratio correction:

$$A_R = 0.75\frac{R}{c} \qquad F_{AR} = \frac{A_R}{A_R+2}$$

Mach number correction:

$$M = \frac{U}{c_s} \qquad F_M = \frac{1}{\sqrt{1-M^2}}$$

Tip loss correction:

$$F_{tiploss} = tanh\left(\frac{1-\frac{r}{R}}{1-\mu}\right)$$

Unsteady aerodynamics:

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\end{bmatrix} = \begin{bmatrix}0 & 1\\ -0.01375\left(\frac{2U}{c}\right)^2 & -0.3455\left(\frac{2U}{c}\right)\end{bmatrix}\begin{Bmatrix}x_1\\ x_2\end{Bmatrix} + \begin{Bmatrix}0\\ 1\end{Bmatrix}\alpha(t)$$

$$C_l(t) = C_{l,\alpha}\left[0.006825\left(\frac{2U}{c}\right)^2 \quad 0.10805\left(\frac{2U}{c}\right)\right]\begin{Bmatrix}x_1\\ x_2\end{Bmatrix} + \frac{C_{l,\alpha}}{4}\alpha(t)$$

Noncirculatory unsteady

aerodynamics:

$$C_{l,nc} = \pi b\left(\frac{\dot{\theta}}{U} + \frac{\ddot{h}}{U^2} - \frac{ba\ddot{\theta}}{U^2}\right)$$

- Inflow correction affects the inflow airspeed U_P
- The unsteady aero terms change the coefficient of lift C_l
- The others are factors on the blade lift ΔL
- Some of these terms may significantly increase computational cost

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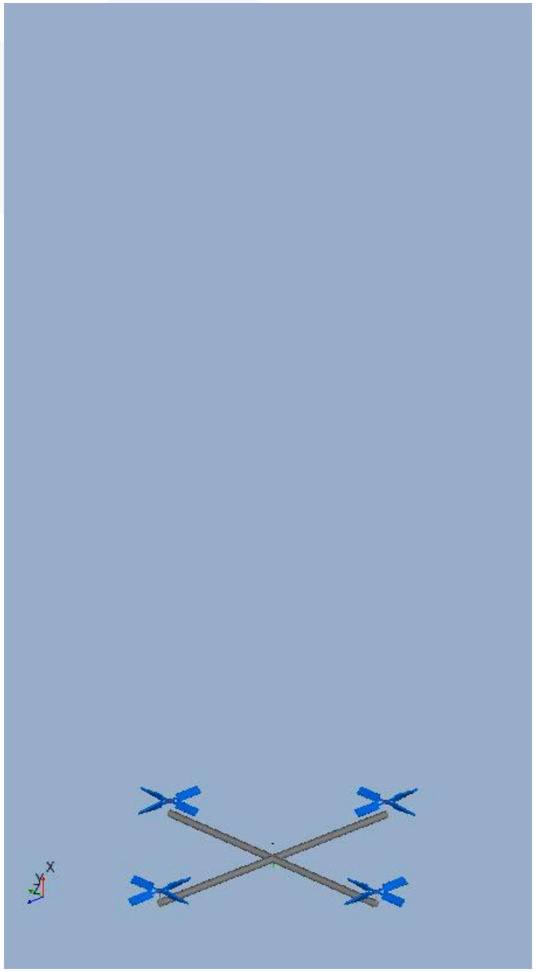
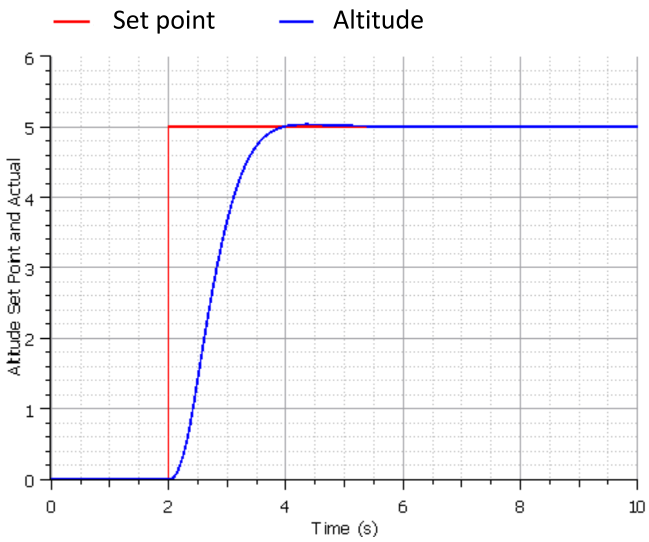
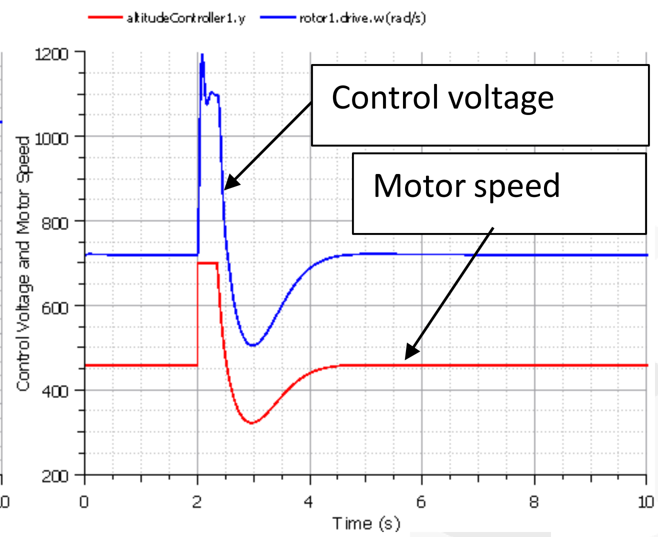
Quadcopter Example

- Couples rotordynamics, multibody dynamics, lifting line aerodynamics, motor electrodynamics
  - Rigid rotors with all but unsteady aerodynamic correction factors
  - Motors are individually voltage-controlled
  - Constrained max motor speed
- Model starts in hover with rotors spun up to counter gravity



Altitude set point starts at zero then steps to 5 m





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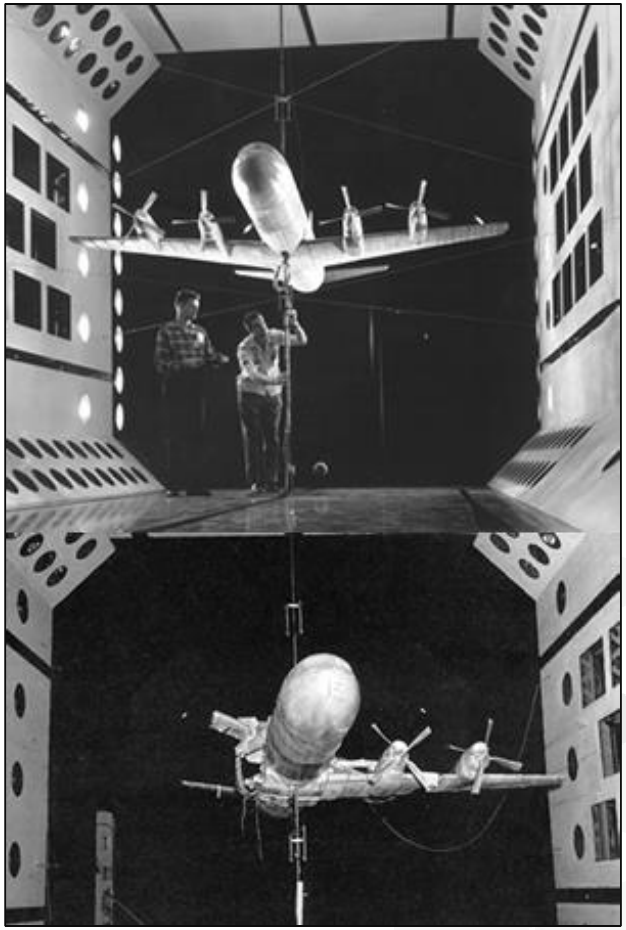
Analysis of Aircraft Whirl Flutter

- Aeroelastic instability caused by the interaction of the aircraft structural dynamics, rotor gyroscopic forces, and rotor aerodynamics
- Initial studies performed in the 60's
  - Houbolt and Reed, Bland and Bennet
  - Driven by early aircraft crashes of Lockheed Electra
  - Interest today in tiltrotor and other non-conventional aircraft
- Directly impacts the aircraft flight envelope

Credit: NASA
https://www.youtube.com/watch?v=j6Q5ggtV-y8



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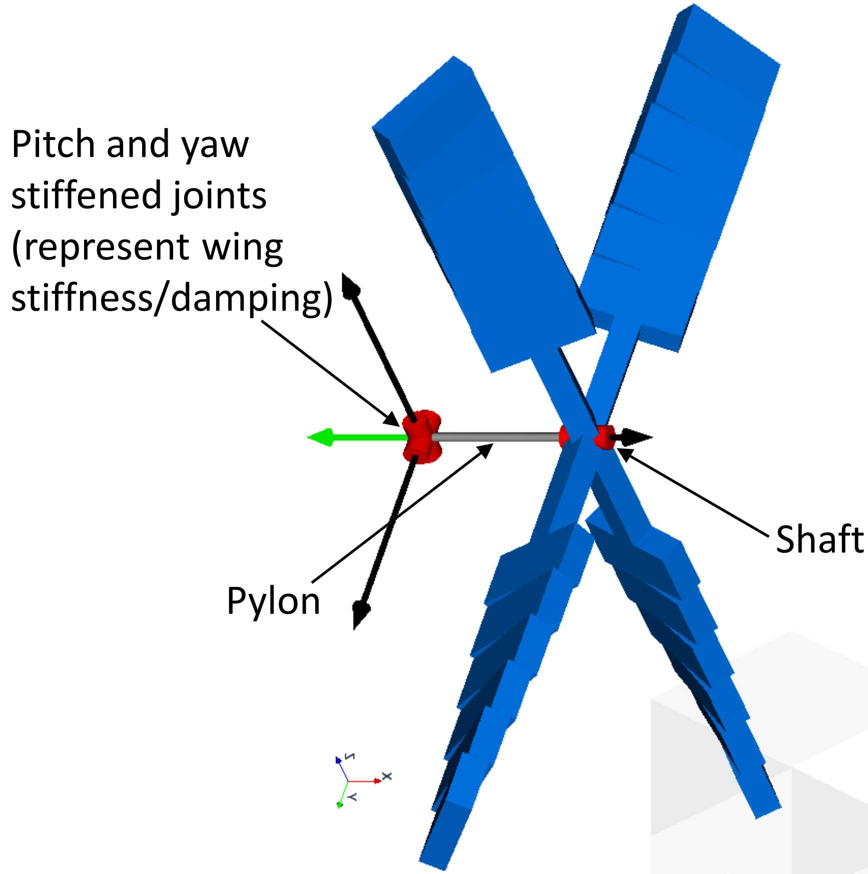
Bland and Bennett Propeller Model Use for Whirl Flutter Analysis

- Modelica model of Bland and Bennett propeller
  - Linearized blade twist
  - Lift-curve slope 5.7/rad
  - Unsteady aerodynamic effects included
  - No in-plane drag
  - 6 airstations per blade
    - Additional airstations showed minimal change in results
- Goal is to find the flutter boundary



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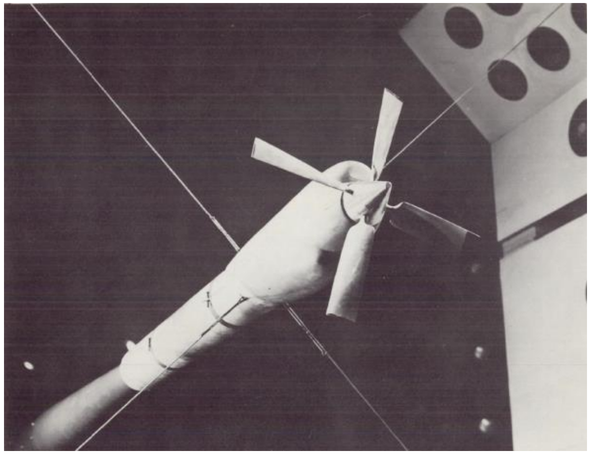
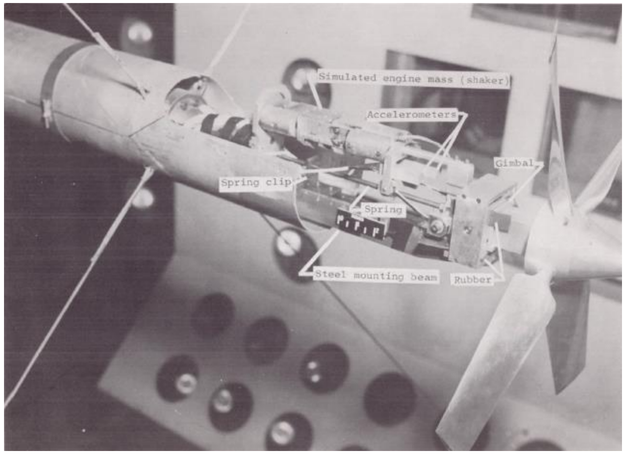
Bland and Bennett Validation Data

- Wind-tunnel whirl flutter measurements taken by Bland and Bennett in 1963 at NASA LaRC Transonic Dynamics Tunnel
- Flutter boundary was determined for various blade pitch angles (β) in a parameter space of reduced velocity/required damping for stability



Source: Bland and Bennett



Source: Bland and Bennett

S.R. Bland and Bennett, R.M., "Wind-Tunnel Measurement of Propeller Whirl-Flutter Speeds and Static-Stability Derivatives and Comparison with Theory", NASA TN D-1807, 1963.

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Verification and Validation – Stability Calculations

- Modelica model is solved with the rotor speed and aerodynamic forces balanced at initialization
  - Linearized system extracted at t=0 sec
- Eigenvalues of linearized system extracted to obtain frequency and damping at an operating point
  - Unstable System (positive real part): **X**
  - Stable System (negative real part): **O**
- Parametric study explored stability within the parameter space of reduced velocity and structural damping
  - Varied damping of springs at base of pylon (i.e., effective wing modal damping) and freestream velocity
  - Performed for a range of fixed blade collectives

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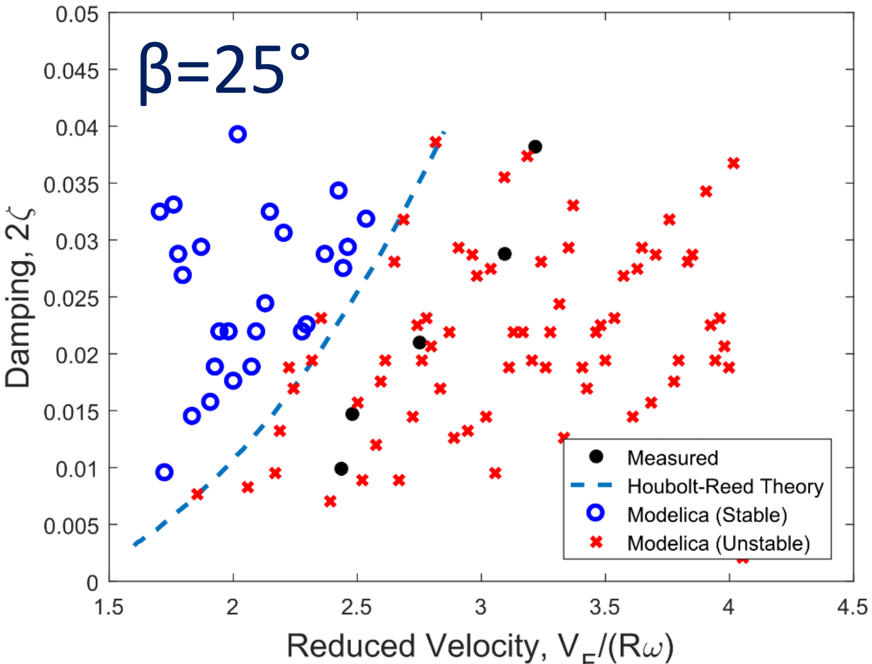
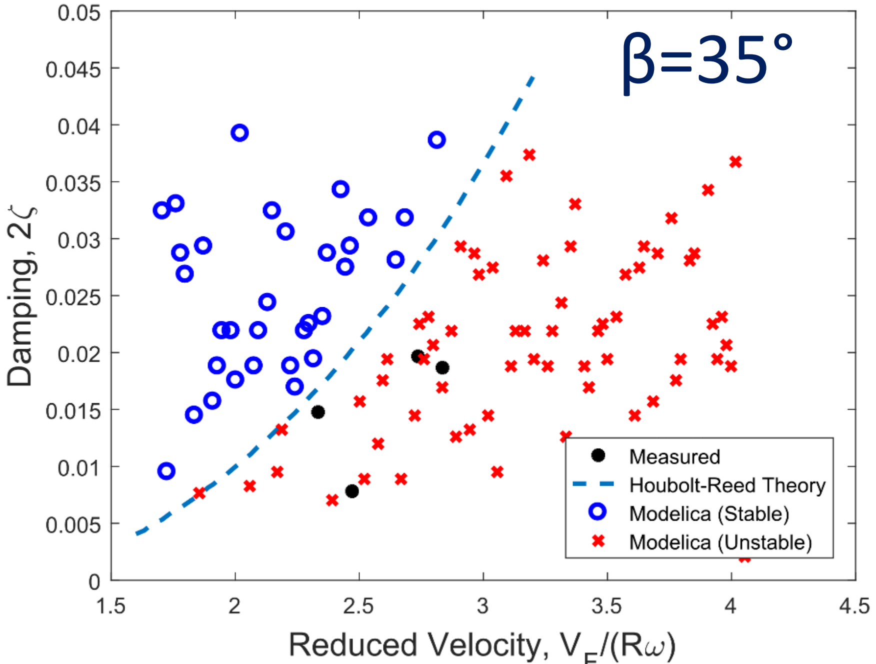
Whirl Flutter Stability Boundaries (1/2)

- Modelica whirl flutter boundary compared to an analytical Houbolt-Reed formulation and measured stability boundary data
- Predictions show good agreement with experimental data and between analysis types despite different formulations





Unstable System: X

Stable System: O

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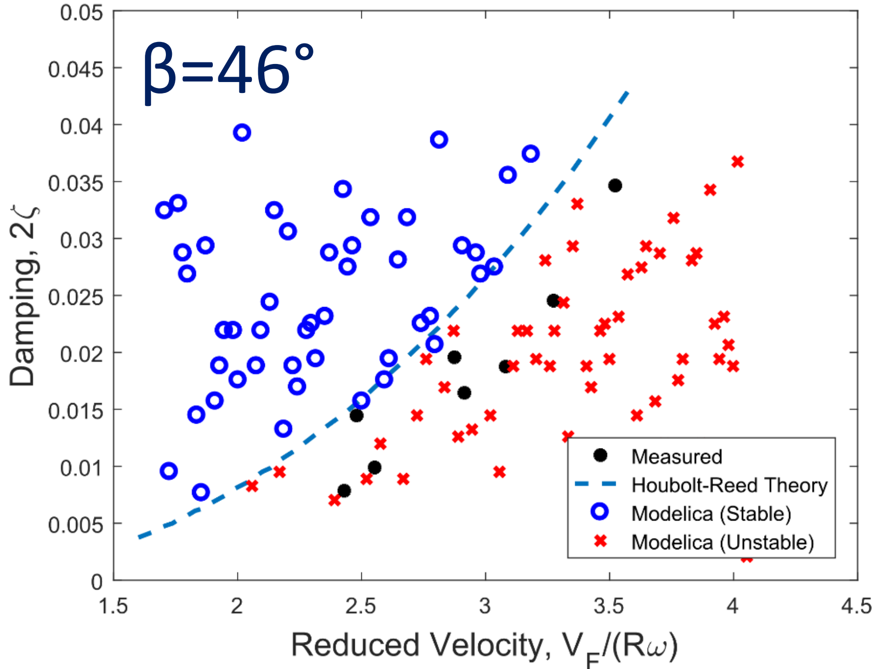
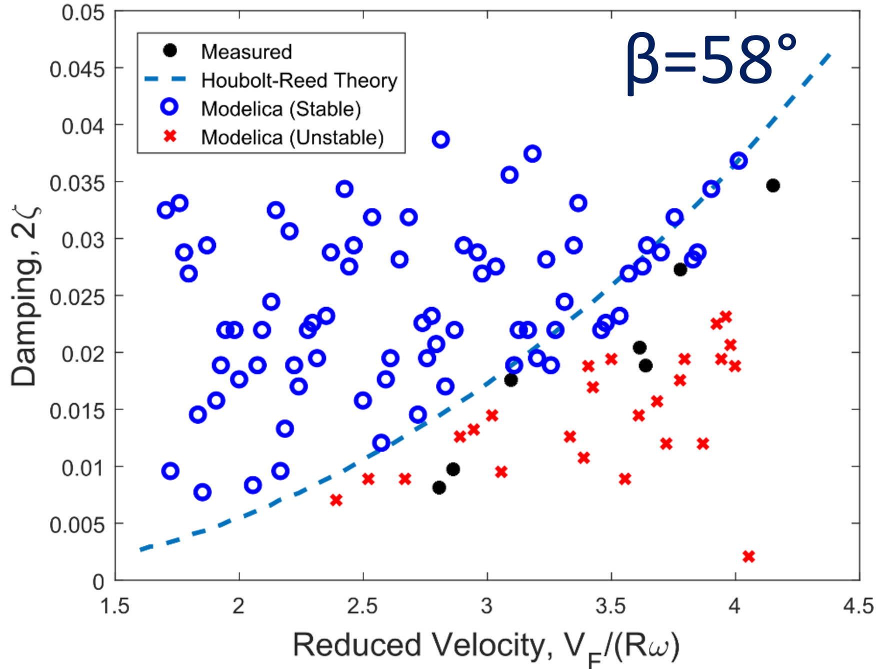
Whirl Flutter Stability Boundaries (2/2)

- At increased blade pitch angles, the Modelica predictions move closer to the experimental results than the analytical boundary
  - Reduced conservatism





Unstable System: X
Stable System: O

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Conclusions

- *RotorAeroLib* enables wide ranging design studies of complex multiphysics phenomena for rotorcraft
- Available on GitHub
  - https://github.com/ATAEngineering/RotorAeroLib
- Developed using OpenModelica
  - Help ensuring compatibility with other compilers would be much appreciated
  - Bug reports and suggestions are always welcome

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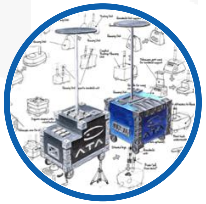
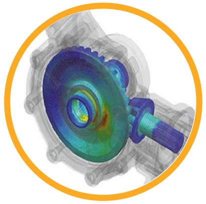


Design

From initial concept development to detailed structural design



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