Large Scale Flutter Data for Design of Rotating Blades using Navier-Stokes Equations

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Project Support : Subsonic Rotary Wing (SRW)
High End Computing (HEC)

Objective

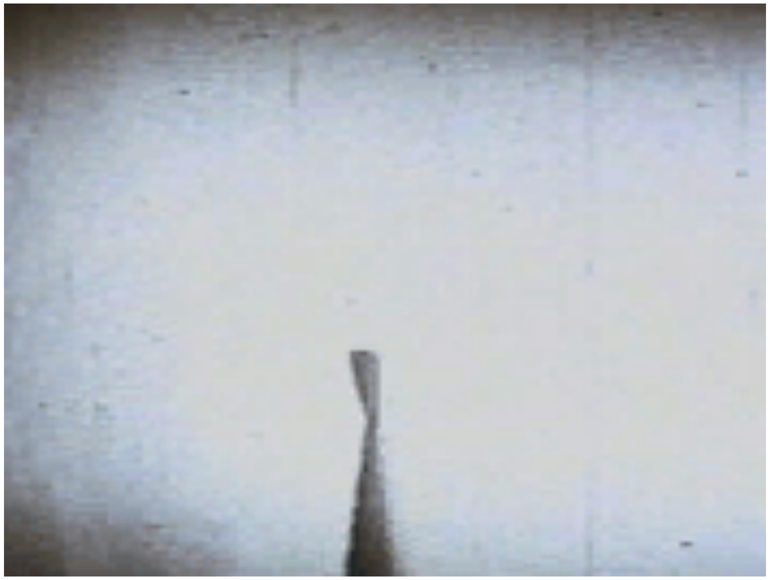
- Demonstrate a procedure to compute flutter data for rotating blades

  - Frequency domain approach
  - Large scale computations
  - Focusing on bending-torsion flutter
  - Navier-Stokes (NS) equations based Computational Fluids Dynamics (CFD) as a tool

Background

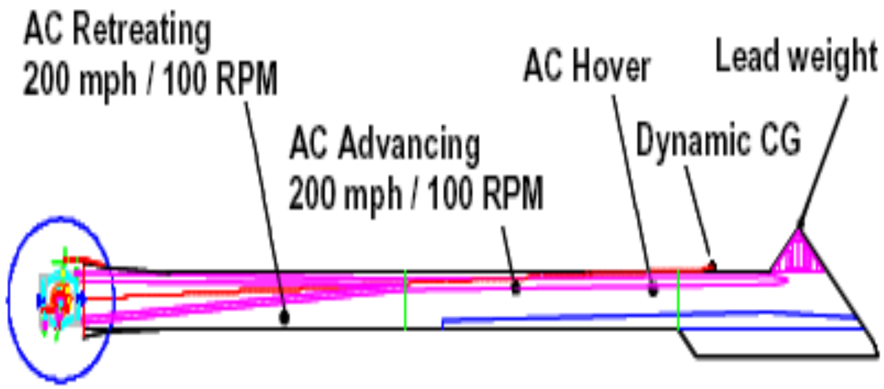
- Bending-torsion flutter for rotating blade can occur
  - while retreating (center of pressure moves back)
  - when flow is transonic (center of pressure moves back)
  - for high advance ratios
  - during stall
- Large number of cases are needed for design
- Current fast procedures for solving flows use linear theory (LT)
- Higher fidelity equations are needed for accuracy
- Efficient use of supercluster is needed for large scale NS based computations

Background (continued)
Bending-Torsion Flutter in Flight



Camera following the blade

Background (continued)
High Advance Ratio (μ~1) Configuration
(Courtesy of Carter Aviation Technologies)



Bending-torsion flutter is an issue during design

Approach

- Flow equations are solved using the OVERFLOW (2.1c & 2.2c) code
  - Reynolds averaged Navier-Stokes (RANS) equations
  - Pulliam-Chausse diagonal form of central difference solver
  - Spalart-Allmaras turbulence model
  - Structured overset grids with 2nd order spatial/temporal accuracy
  - Well validated for unsteady flow calculations
  - 1-D prescribed modal motion interface (AIAA 2012-4789)
- Lagrange's structural equations of motion solved using FLUMOD
  - Modal form
  - Frequency domain
- Intial validation using
  - Kernel Function and Doublet-Lattice based linear aero methods
  - Experiments for fixed blades
  - Comparison with fixed blade flutter
- Use CFD grids previously validated for steady flows
  (Doug Boyd, AHS 56 May 2009, Guruswamy J of Aircraft, May 2010)

U-g method
(Velocity-damping)

- Assumes linear-superposition of modes similar to that in reduced-order modeling (ROM) methods
- Predicts on-set of flutter
- Built-in procedure in NASTRAN using doublet-lattice and Mach box linear aerodynamic theories

  - Routinely used by aerospace industry

- Extensively applied for fixed wings using NS equations

Frequency Domain Formulation

- **With [Φ] as modal matrix, displacements are expressed as**

$$\{d\} = [\Phi]\{h\}$$

- **Generalized displacements at flutter are** $\{h\} = \{\bar{h}\}e^{\omega(1+ig)t}$

ω = circular frequency, **g** = structural damping; **t** = time

- **Complex Eigenvalue Eqn for bending** $\bar{h}_1$ **and torsion** $\bar{h}_2$

$$\eta k_r^{\,2}\left[[M]-[A]\right]\{\bar{h}\} = \lambda[K]\{\bar{h}\}$$

Air-Mass Ratio $\eta = M_{11}/(\pi\rho R c^2)$ **Reduced Freq** $k_r = 4\omega c/3\Omega R$

Eigen-Value $\lambda = \eta(1+ig)\omega_f^2 c^2/4S^2$ **;** **Flutter Speed** $S = 2U/c\omega_2$

Ω = rotation speed; $\boldsymbol{\omega_1, \omega_2, \omega_f}$ = bending, torsion, flutter freq
[M] = mass; **[K]** = stiffness.; **c** = chord; **U** = velocity; **R** = radius

- **[A] = aerodynamic matrix computed using RANS solver**

Aerodynamic Coefficients from RANS Solver

$$A_{11} = \int_0^R C_{l\delta} \Phi_1^2 \delta r \qquad A_{12} = \int_0^R C_{l\alpha} \Phi_1 \Phi_2 \delta r$$

$$A_{21} = \int_0^R C_{m\delta} \Phi_2 \Phi_1 \delta r \qquad A_{22} = \int_0^R C_{m\alpha} \Phi_2^2 \delta r$$

Φ_1 and Φ_2 are bending and torsion modes, respectively

$C_{l\delta}(r) =$ **Lift due to bending mode**

$C_{l\alpha}(r) =$ **Lift due to torsion mode**

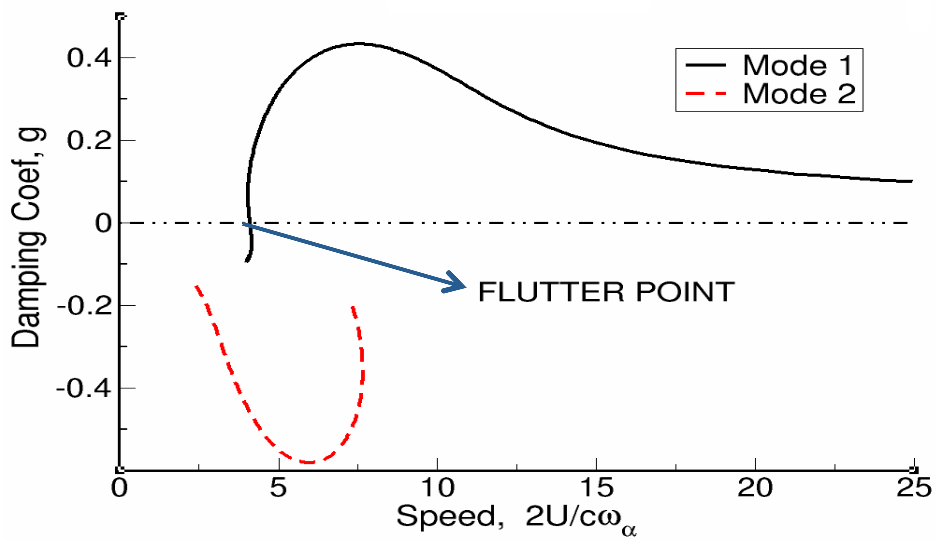
$C_{m\delta}(r) =$ **Moment due to bending mode**

$C_{m\alpha}(r) =$ **Moment due to torsion mode**

Flutter Solution Procedure

- Compute force responses for 2 modes and various frequencies at a given rotating speed (Ω)
- Compute real/imaginary values of forces from Fourier analysis
- Solve Eigen-Value equation by varying the frequency and tracking *g*
- Extract flutter point when *g* changes sign

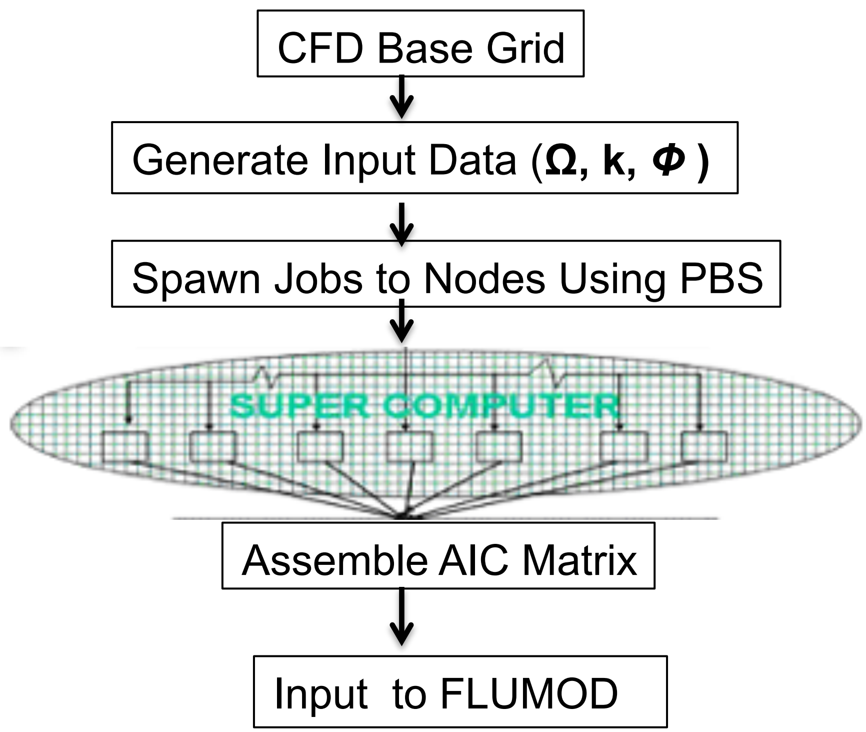
Typical U-g plot



Parallel Computational Procedure

- **Massively parallel computations**
- **Single job submission script to run all cases at same time using portable batch system (PBS)**

GENMOD



Typical Timings

- 25 wall-clock hrs to run up to 1000 responses for flexible wing

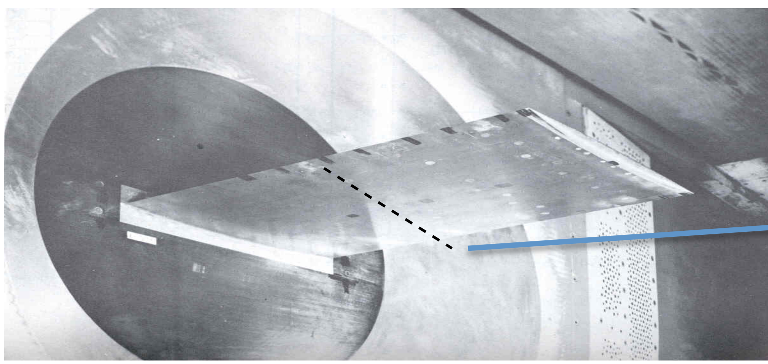
VALIDATION AND DEMONSTRATIONS

Validation of Unsteady Pressures

Non-Rotating blade, M_∞= 0.90, Reduced Freq. = 0.26, Re = $2.1x10^6$

Computations

- C-H grid, 253K (151x35x48)
- 2400 time steps per cycle
- results at 4th cycle
- data taken at 50% with no wall viscous effects

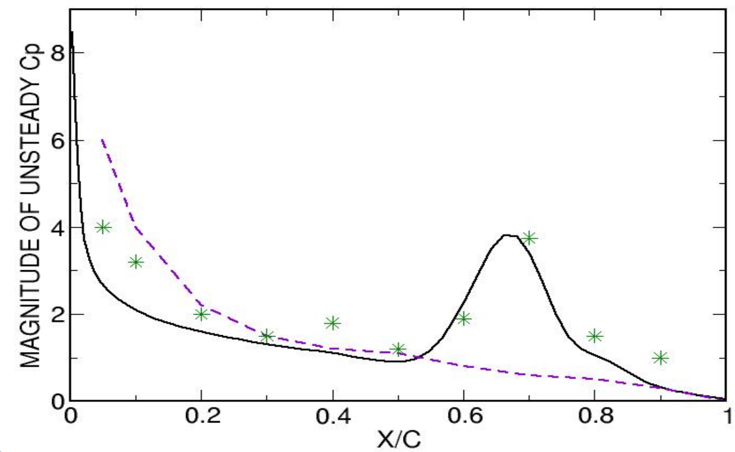


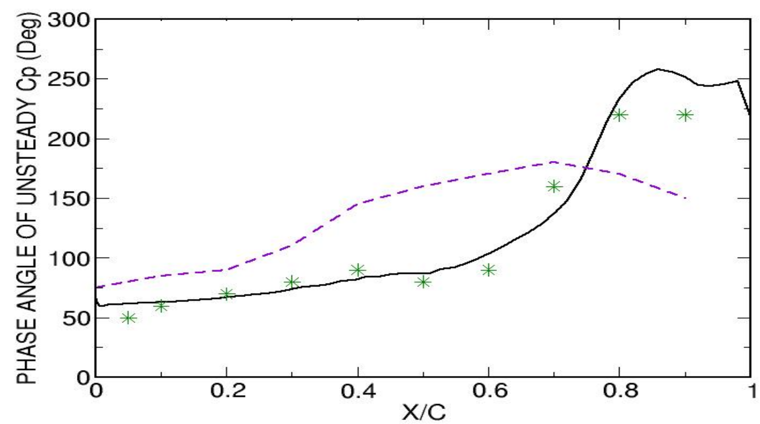
NASA TND-344 (1960,ARC)

6% thick parabolic arc, Aspect Ratio = 5
Blade oscillating in first flapping mode

Unsteady Cp at 50% Semispan

RANS
Linear Theory
* Experiment (NASA TND-344)





Validation of Flutter Boundary

Non-rotating aeroelastic rectangular wing, Re = 4.5×10^6

NASA TMX -79 (1959, LaRc), 6% Parabolic Arc, Aspect Ratio = 5

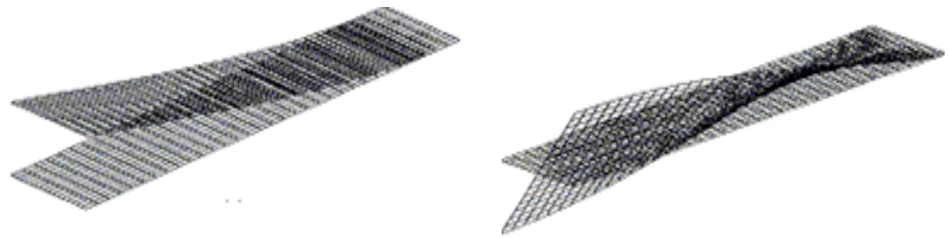
Computations

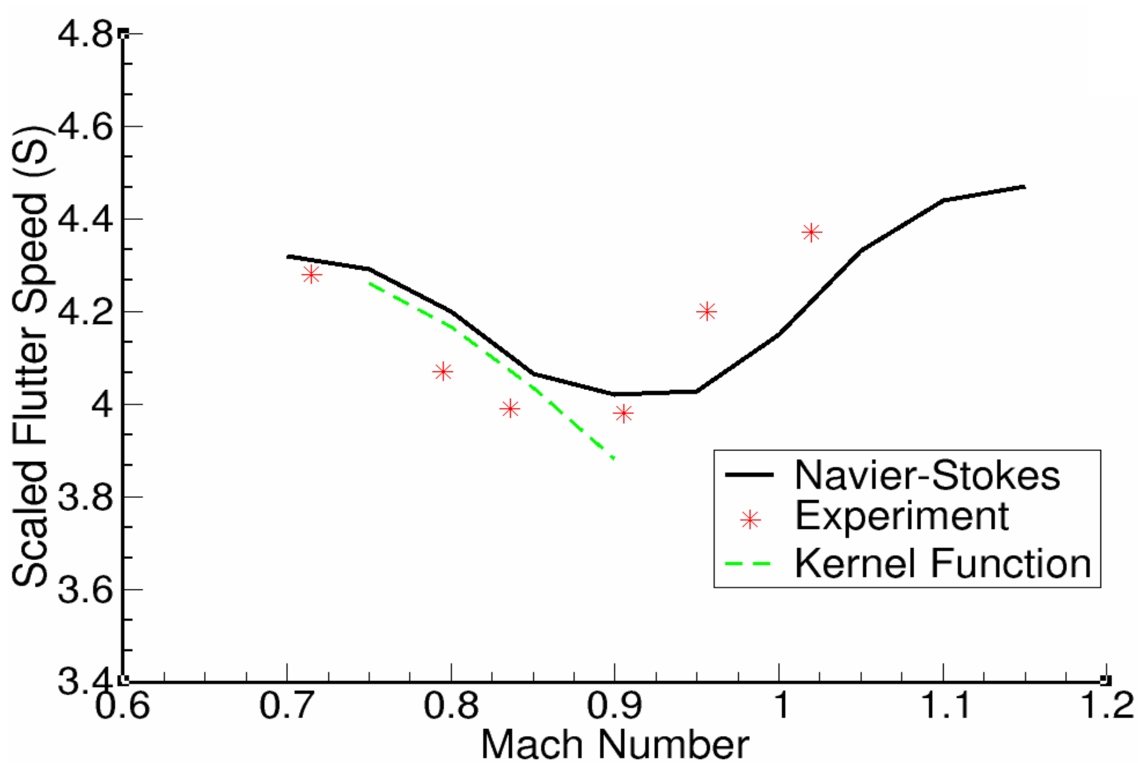
- C-H grid, 253K points (151x35x48)
- 2400 steps per cycle
- 4 oscillations
- 2 modes, 5 frequencies, 10 Mach numbers

Kernel Function

- NASA TP-2292 (1984)

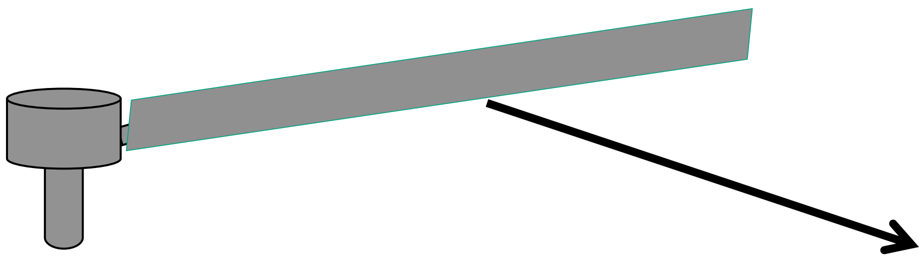
Modes

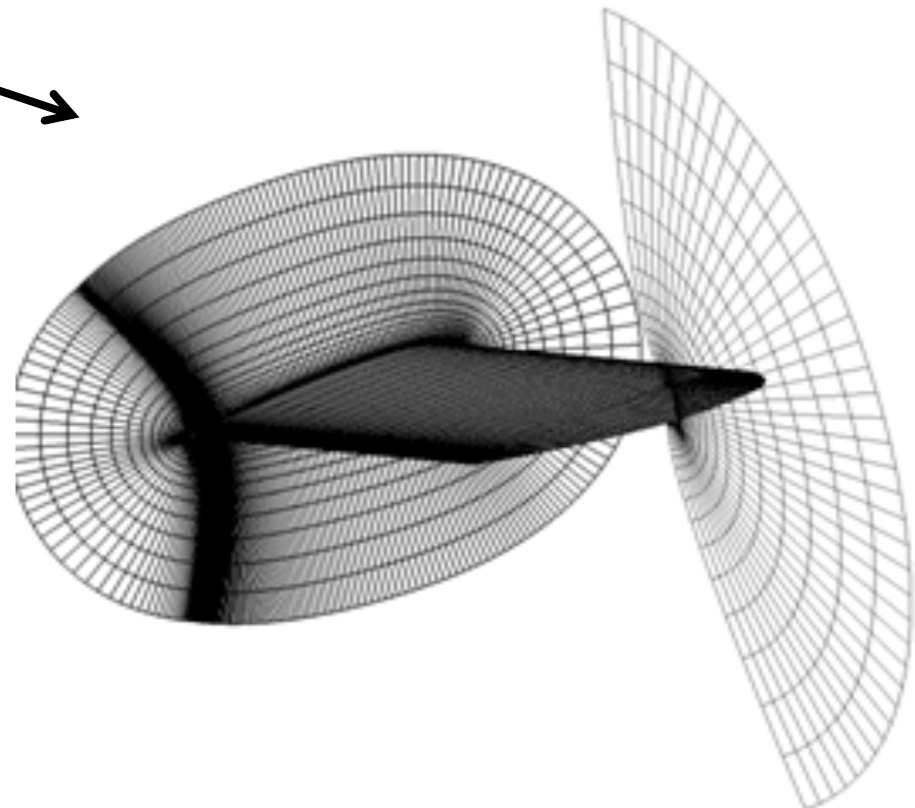




Demonstration for Single Rotating Blade

Hover, θ_c = 10 deg, Aspect ratio =16, NACA23012, Re = 15×10^6





Grid
- Doug Boyd, 56th AHS, 2009
- 1.8×10^6, 3 near body blocks
- outer boundaries ~10 chords

Structural Properties

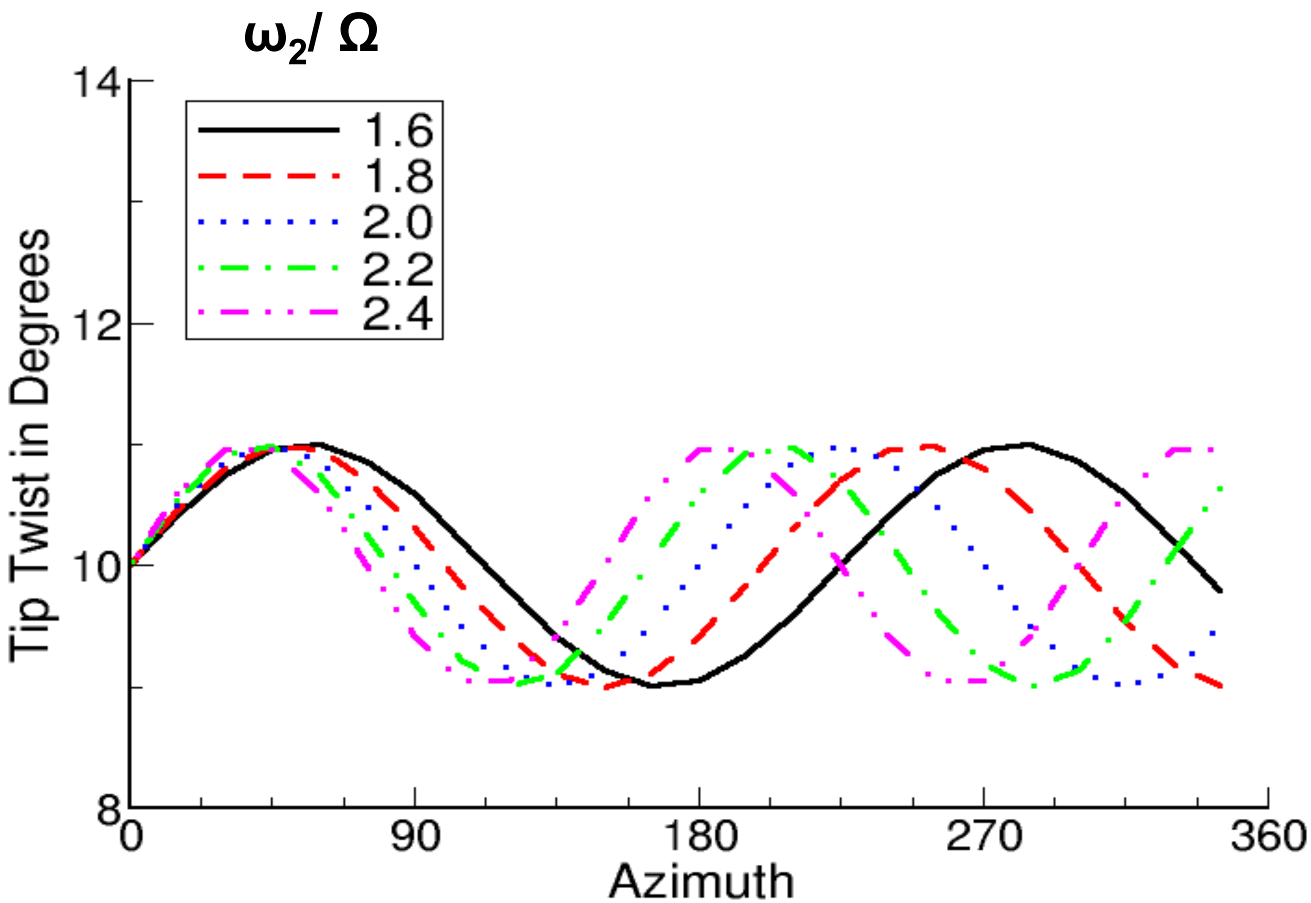
$\omega_1 / \omega_2 = 0.30$

mass center = 45% chord

elastic axis = 25% chord

Cases - 100
- 10 rotating speeds
- 2 modes
- 5 frequencies

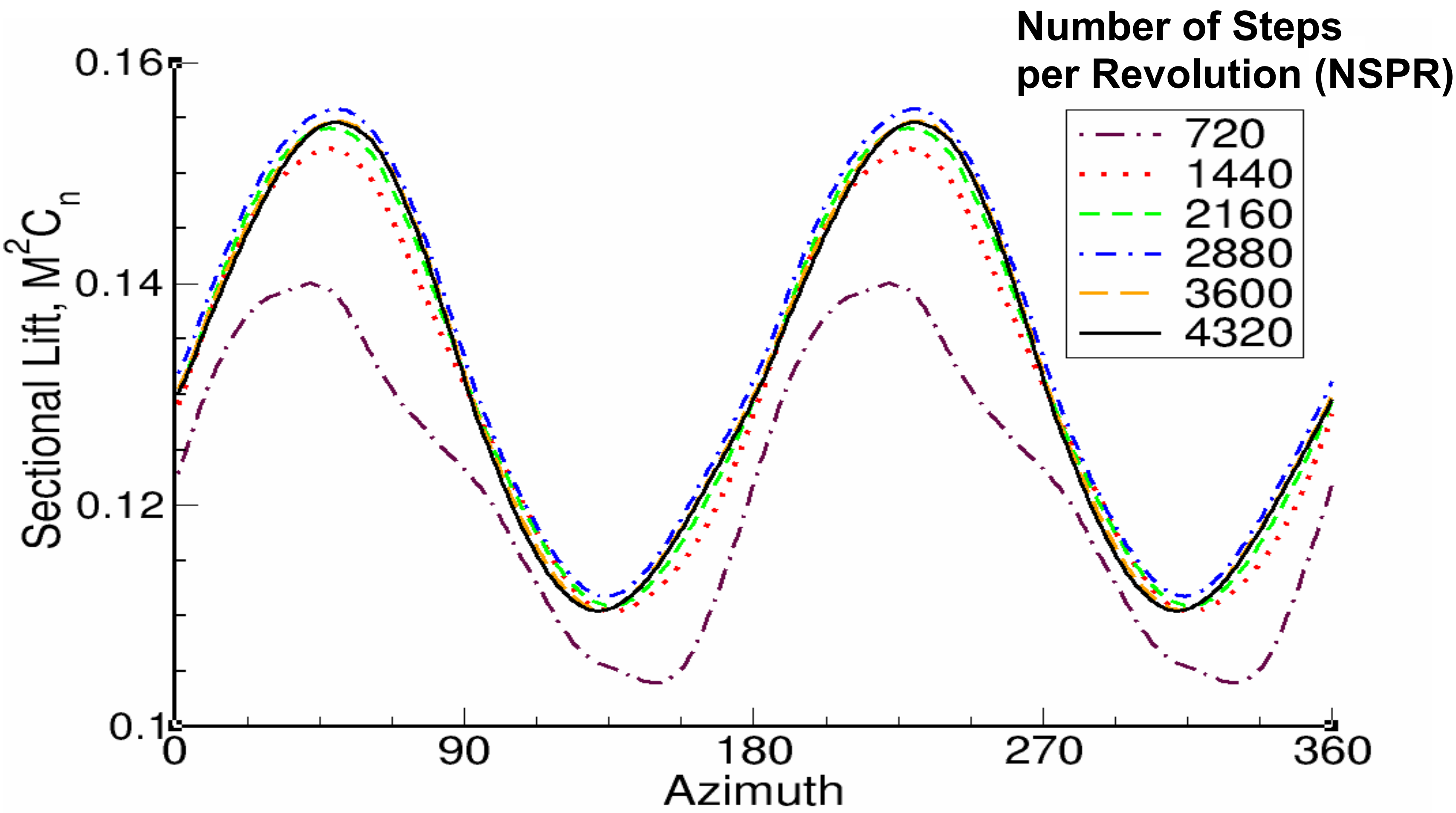
Twist Modes



$\omega_2/\ \Omega$
1.6
1.8
2.0
2.2
2.4
Tip Twist in Degrees
14
12
10
8
0
90
180
270
360
Azimuth

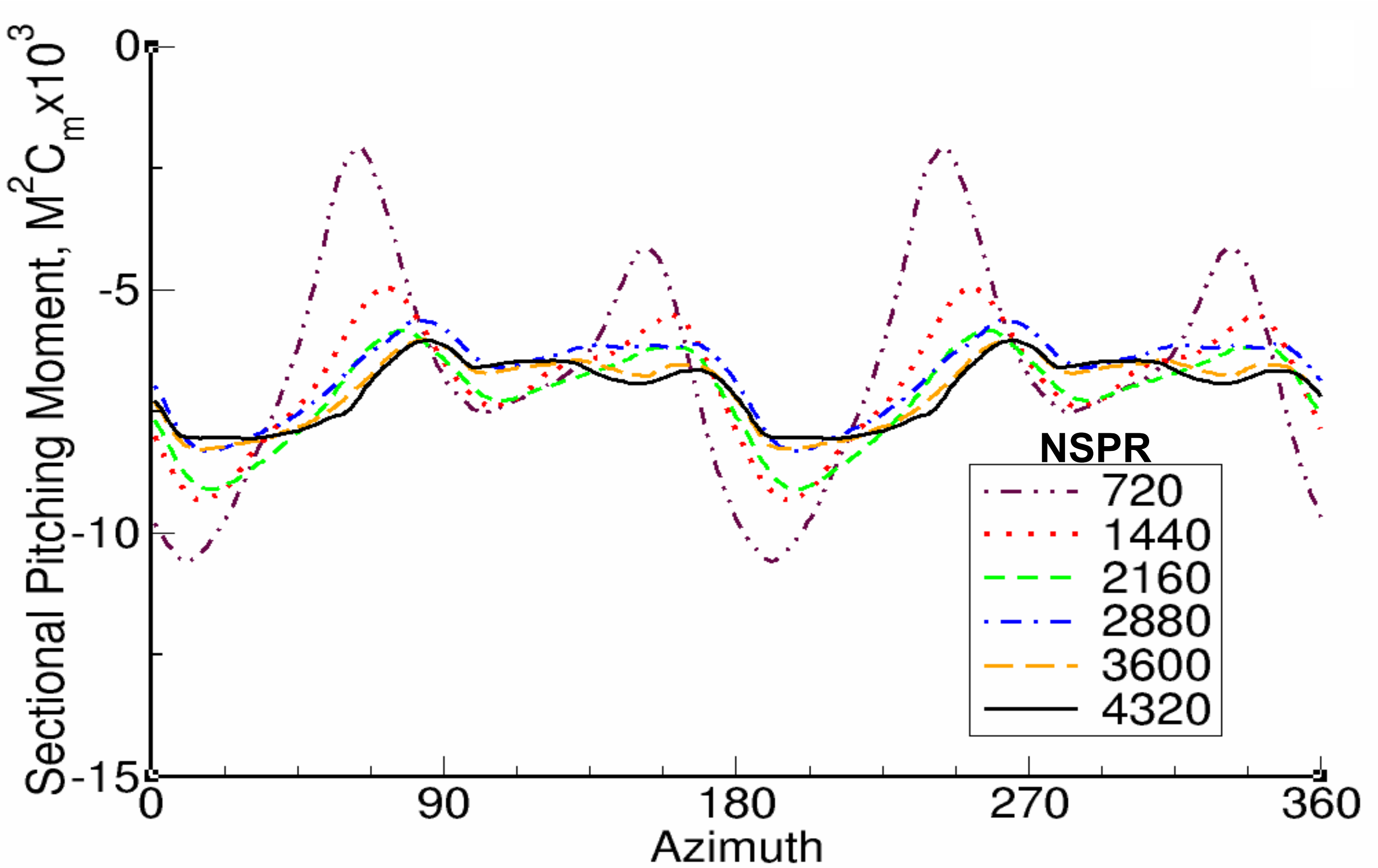
Time Step Convergence of Sectional Lift

ω_2/Ω = 2.0, 4th Revolution , 85% radial station



Time Step Convergence of Pitching Moment

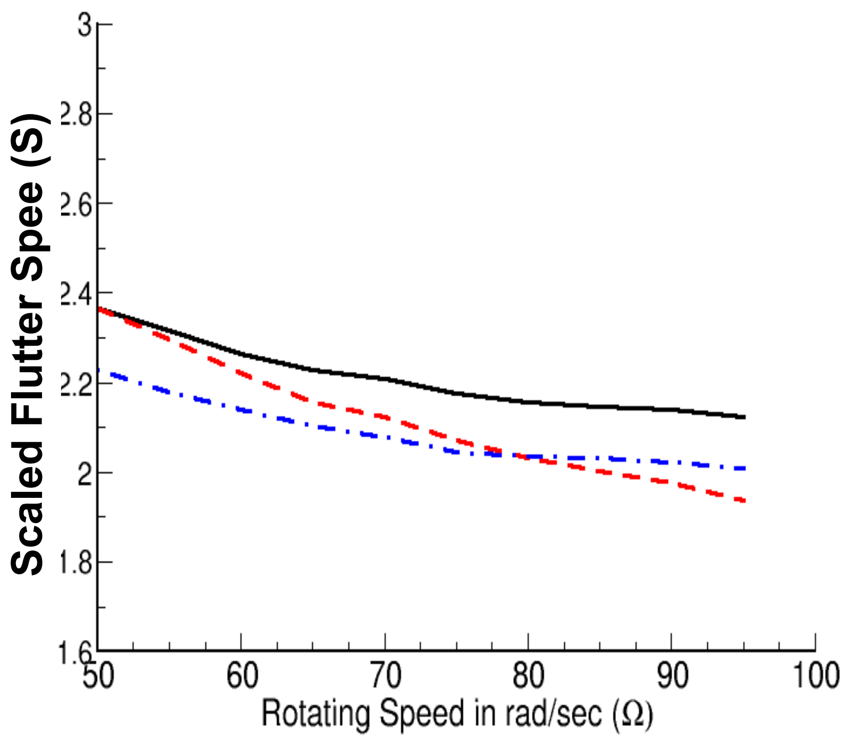
ω_2/Ω = 2.0, 4th Revolution, 85% radial station

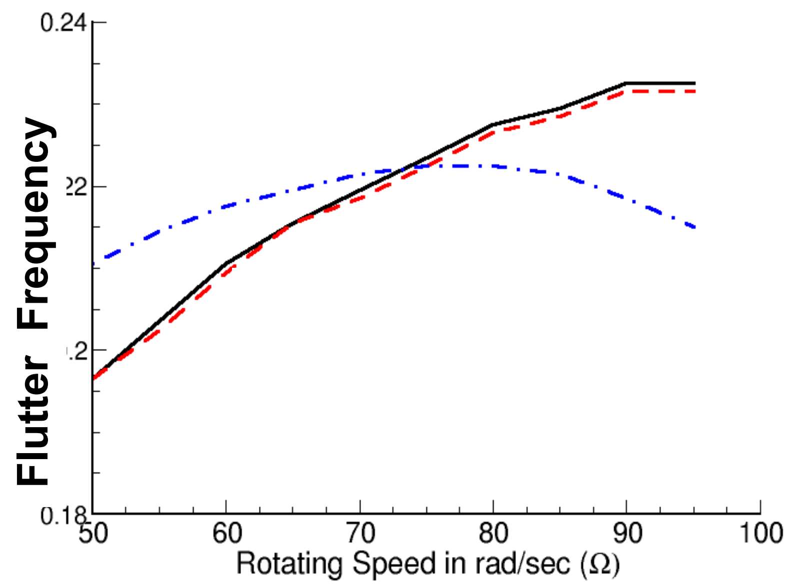


Flutter Boundary for a Rotating Blade

- **100 responses with 4 revolutions using NSPR = 3600**
  - **Each case is assigned to one core, 24 hr wall clock time**

Rotating **Rotating (Constant Stiffness)** **Non-Rotating**





Summary

- A procedure to compute flutter boundaries of rotating blades is presented
  - Navier-Stokes equations
  - Frequency domain method compatible with industry practice

- Procedure is intially validated
  - Unsteady loads with flapping wing experiment
  - Flutter boundary with fixed wing experiment

- Large scale flutter computation is demonstrated for rotating blade
  - Single job submission script
  - Flutter boundary in 24 hour wall clock time with 100 cores
  - Linearly scalable with number of cores. Tested with 1000 cores that produced data in 25 hrs for 10 flutter boundaries.

- Further wall-clock speed-up is possible by performing parallel computations within each case
  – work in progress