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
- Initial 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 $[\Phi]$ as modal matrix, displacements are expressed as
  \[ \{d\} = [\Phi] \{h\} \]

- Generalized displacements at flutter are $\{h\} = \{\vec{h}\} e^{\omega(1+ig)t}$
  \[ \omega = \text{circular frequency}, \quad g = \text{structural damping}; \quad t = \text{time} \]

- Complex Eigenvalue Eqn for bending $\vec{h}_1$ and torsion $\vec{h}_2$
  \[ \eta k_r^2 [\{M\} - [A]]\{\vec{h}\} = \lambda [K] \{\vec{h}\} \]

  - 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 $S = 2U/c\omega_2$

  - $\Omega$ = rotation speed; $\omega_1, \omega_2, \omega_f$ = 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

\[ A_{11} = \int_{0}^{R} C_{l\delta} \phi_{1}^{2} \delta r \]
\[ A_{12} = \int_{0}^{R} C_{l\alpha} \phi_{1} \phi_{2} \delta r \]
\[ A_{21} = \int_{0}^{R} C_{m\delta} \phi_{2} \phi_{1} \delta r \]
\[ A_{22} = \int_{0}^{R} C_{m\alpha} \phi_{2}^{2} \delta r \]

\( \Phi_{1} \) and \( \Phi_{2} \) 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 ($\Omega$)
- 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](image)
Parallel Computational Procedure

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

GENMOD

- CFD Base Grid
- Generate Input Data \((\Omega, k, \Phi)\)
- Spawn Jobs to Nodes Using PBS
- Assemble AIC Matrix
- Input to FLUMOD

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, $M_\infty = 0.90$, Reduced Freq. = 0.26, $Re = 2.1 \times 10^6$

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

Unsteady Cp at 50% Semispan

- RANS
- Linear Theory
- Experiment (NASA TND-344)

NASA TND-344 (1960, ARC)
6% thick parabolic arc, Aspect Ratio = 5
Blade oscillating in first flapping mode
Validation of Flutter Boundary
Non-rotating aeroelastic rectangular wing, Re = 4.5x10^6
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
Demonstration for Single Rotating Blade

Hover, $\theta_c = 10$ deg, Aspect ratio =16, NACA23012, Re = $15 \times 10^6$

Grid
- Doug Boyd, 56th AHS, 2009
- $1.8 \times 10^6$, 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

$\omega_2/\Omega$

Tip Twist in Degrees

Azimuth

$\omega_2/\Omega$

- 1.6
- 1.8
- 2.0
- 2.2
- 2.4
Time Step Convergence of Sectional Lift

$\omega_2/\Omega = 2.0$, $4^{th}$ Revolution, 85% radial station

Number of Steps per Revolution (NSPR)

- 720
- 1440
- 2160
- 2880
- 3600
- 4320

Sectional Lift, $M^2 C_n$ vs Azimuth
Time Step Convergence of Pitching Moment

$\omega_2/\Omega = 2.0$, 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

Graphs showing:
- Scaled Flutter Speed (S)
- Flutter Frequency

Rotating (black line), Rotating (Constant Stiffness) (red dashed line), Non-Rotating (blue dashed line)
Summary

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

- Procedure is initially 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