AePW-2: FUN3D Results

Pawel Chwalowski and Jennifer Heeg
Aeroelasticity Branch, NASA Langley Research Center, Hampton, Virginia

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Acknowledgments

- Robert Biedron, Bil Kleb, Beth Lee-Rausch, and Eric Nielsen from the Aerosciences Branch at NASA Langley
- Steve Massey from Aeroelasticity Branch
- Dave Schuster from NESC
- NAS, NASA Advanced Supercomputing Center
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<tr>
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<th>Case 1</th>
<th>Case 2</th>
<th>Optional Case 3</th>
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<td>0.74</td>
<td>0.85</td>
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<tr>
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Established as a research code in late 1980s; now supports numerous internal and external efforts across the speed range
- Solves 2D/3D steady and unsteady Euler and RANS equations on node-based mixed element grids for compressible and incompressible flows
- General dynamic mesh capability: any combination of rigid / overset / morphing grids, including 6-DOF effects
- Aeroelastic modeling using mode shapes, full FEM, etc.
- Constrained / multipoint adjoint-based design and mesh adaptation
- Distributed development team using agile/extreme software practices including 24/7 regression, performance testing
- Capabilities fully integrated, online documentation, training videos, tutorials
Some Recent NASA Applications

Aeroelastic Analysis of the Boeing SUGAR Truss-Braced Wing Concept

Open-Rotor Concepts

Courtesy Bob Bartels

Courtesy Bill Jones
Some Recent NASA Applications

Transonic Buffet Characterization for Space Launch System

Courtesy Greg Brauckmann, Steve Alter, Bil Kleb
Some Recent NASA Applications

Distributed Electric Propulsion

Courtesy
Mike Park, Sally Viken,
Karen Deere, Mark Moore

Courtesy Bill Jones
FUN3D and High-Performance Computing

**FUN3D is used on a broad range of HPC installations around the country**

![Image of HPC installation](image)

Scaled to 80,000 cores

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http://fun3d.larc.nasa.gov

FUN3D Training Workshop
June 20-21, 2015
FUN3D Aeroelastic Capabilities

- Built upon elasticity PDE-based mesh deformation
- Built in modal structural solver, same as in CAP-TSD, CFL3D, Overflow
  - Typically uses mode shapes from NASTRAN normal modes analysis
- Coupling to external FEM/CSD codes
  - Read surface displacements obtained from FEM
  - Write aerodynamic loads \((C_p, C_{fx}, C_{fy}, C_{fz})\) for FEM
  - Requires CFD/CSD transfer middleware
  - Special case: rotorcraft comprehensive CSD codes, CAMRAD, DYMORE
Model the mesh as a linear elastic solid governed by

\[ \nabla \cdot \left[ \mu (\nabla u + \nabla u^T) + \lambda (\nabla \cdot u) I \right] = f = 0 \]

\[ \frac{E}{(1 + \frac{1}{V})} = \frac{E}{2(1 + \frac{1}{d})} \]

Choose Poisson’s ratio and Young’s modulus to close system

- \( \mu \) constant, \( E = E(1/V) \) or \( E(1/d) \)
- Smaller cells or cells closer to surface are stiffer

Solve linear PDE

- Large fraction (typ. 30% or more) of cost of flow-solver step
- Eventually will employ multigrid to speed up solution

Geometric Conservation Law (ALE formulation) accounted for

- Essential for free stream preservation on deforming meshes
- Appears as a source term in flow equation residuals
Unforced steady state solution → Unforced unsteady solution → Static aeroelastic solution, Forced unsteady solution with large structural damping value (0.999) → Dynamic aeroelastic solution, Forced unsteady solution with small structural damping value (0.0) and initial generalized Vel.
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AePW-2 Case 2, Mach 0.74, AoA = 0°

Predicted flutter onset: $q = 152$ psf and $f = 4.23$ Hz
AePW-2 Case 2, Mach 0.74, AoA = 0°
AePW-2 Case 2, Mach 0.74, AoA = 0°
AePW-2 Case 2, Mach 0.74, AoA = 0°, q=169 psf
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AePW-2 Case 3B, Mach 0.85, AoA = 5°
## AePW-2 Case 3C, Mach 0.85, AoA = 5°

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### AePW-2 Case 3C, Mach 0.85, AoA = 5°

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<th>Mesh / Turb. Model</th>
<th>Flutter dynamic pressure, psf</th>
<th>Flutter frequency, Hz</th>
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<tr>
<td></td>
<td>No Limiter</td>
<td>Limiter</td>
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<tr>
<td>Coarse / SA</td>
<td>455</td>
<td>665</td>
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<tr>
<td>Medium / SA</td>
<td>477</td>
<td>503</td>
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<td>Fine / SA</td>
<td>390</td>
<td>482</td>
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<tr>
<td>Fine / DDES</td>
<td>565</td>
<td>x</td>
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Note: Venkatakrishnan Limiter
AePW-2 Case 3C, Mach 0.85, AoA = 5°

Static aeroelastic solution at q’s near flutter onset: fine grids
Flutter Onset at AoA = 5°, Coarse Grid, No Limiter
AePW-2 Case 3C, Mach 0.85, AoA = 5°

Static aeroelastic solutions: Skin friction and streamlines at dynamic pressure near flutter onset

Mach 0.82

Mach 0.80

Mach 0.85
AePW-2 Case 3C, Mach 0.85, AoA = 5°

Q = 204 psf

Q = 816 psf

Upper surface

Lower surface
Conclusions

- It takes too long and significant computational resources are required to obtain flutter boundary prediction on a simple configuration like BSCW.
- There is need for tools like Reduced Order Methods to obtain flutter boundary prediction quickly.
- Spatial and temporal convergence analysis are necessary.
- 2D airfoil section analysis vs. 3D analysis.
Backup
FUN3D Analysis, Medium Grid, Mach 0.82, Steady Rigid Analysis
60% span station

Skin Friction Coefficient, Streamwise direction (CFx)

$\frac{x}{c}$

Cp

$\frac{x}{c}$
FUN3D Analysis, Medium Grid, Mach 0.70, Steady Rigid Analysis
60% span station

Skin Friction Coefficient (Cf)

-1 deg, Upper Surface
0 deg, Upper Surface
1 deg, Upper Surface
3 deg, Upper Surface
5 deg, Upper Surface
-1 deg, Lower Surface
0 deg, Lower Surface
1 deg, Lower Surface
3 deg, Lower Surface
5 deg, Lower Surface

Cp

-2
-1.5
-1
-0.5
0
0.5
1
0
0.2
0.4
0.6
0.8
1
x/c