Wing Flutter Computation Using Modified Spectral Volume Method

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Outline

- Background
- Objective
- Spatial discretization method
- Validation of present code
  - Unsteady flowfield over NACA0012 airfoil in pitching motion
- Flutter computation
  - AGARD445.5 weakened wing
- Summary
- Future works
Transonic Flutter

- Self oscillation caused by aerodynamic, elastic and inertial forces
- Easy to occur in case of high aspect ratio, thin wing and low stiffness material
- Wing may be broken

Examination of flutter characteristics is getting more and more important

Numerical flutter analysis by JAXA


Distribution of materials on B787

http://www.mech.nias.ac.jp

using composite materials

stiffness decreases

Examination of Flutter Characteristics

- Wind tunnel test
- **Numerical analysis**

Analysis assuming **linear** aerodynamic force
- Cannot consider shock wave
- Computational cost is lower

Pursue performance with flutter margin

Analysis assuming **non-linear** aerodynamic force
- Can consider shock wave
- Computational cost is higher
- Reduce number of wind tunnel tests
Objective

- Develop fluid-structure interaction code
  - CFD code development
    - ALE formulation for moving grid
    - Extend conventional SV method to hybrid unstructured mesh
  - Code validation
    - Unsteady flowfield over NACA0012 airfoil in pitching motion
  - Flutter computation
    - AGARD445.6 weakened wing
Conventional Spectral Volume Method

- Finite volume method
- High order unstructured grid method

Tetrahedral cell (Spectral Volume (SV))

Further subdivided

4 hexahedral cells (Control Volume (CV))

• Governing equations are solved in each CV
• Distribution of variables in SV is written by high order polynomial consists of 4 CV cell average values

Reconstructed polynomial: \( \tilde{Q}(\xi, \eta, \zeta) = \sum_{j}^{4} L_j(\xi, \eta, \zeta) \bar{Q}_j \)

Shape function: \( L_j(\xi, \eta, \zeta) = c_j^1 \xi + c_j^2 \eta + c_j^3 \zeta + c_j^4 \)
Modified SV Method for Flutter Analysis

- Arbitrary Lagrangian-Eulerian (ALE) formulation for moving grid
- Extended to utilize hybrid unstructured meshes
  - Conventional SV utilizes only tetrahedral cells (4DOFs)
  - Although number of DOFs is increased in each cell other than tetrahedral cells, the total number of computational cells can be substantially reduced
  - Convergence rate is significantly improved by introducing prismatic cell layers on the solid wall
  - Truly second order even for skewed unstructured meshes
  - Adaptive mesh refinement is easily devised by hierarchical subdivision of control volume

![Convergence histories for turbulent boundary layer over flat plate](image)
Validation of Present Code on Moving Grid

• Unsteady flowfield over NACA0012 airfoil in pitching motion
  - Compared with Landon’s experiment
Numerical Methods

Governing equations: 3D Euler/RANS equations
Spatial discretization: 2nd order modified SV method
Numerical flux: SLAU
Viscous term gradient: BR2 method
Time integration: 2nd order backward difference formula (BDF2)
Implicit method: LU-SGS method with inner iteration
Turbulence model: Spalart-Allmaras model
Computational Grids

- **Euler**
  - Hexahedrons: 19,720
  - Computational domain: 30 chord

- **RANS**
  - Hexahedrons: 28,500
  - Computational domain: 30 chord
  - Off wall spacing: $5.6 \times 10^{-6}$
    ($y^+ = 1$)
Computational Conditions

- **Free stream condition**
  - Mach number: 0.6
  - Reynolds number: \(4.8 \times 10^6\)

- **Criteria for ending inner iteration**
  - \(\Delta \rho < 10^{-7}\)

- **\(\Delta t\), CFL, inner iterations**

<table>
<thead>
<tr>
<th>Method</th>
<th>CFL((\Delta t))</th>
<th>Inner iteration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Euler</td>
<td>300(0.05)</td>
<td>25</td>
</tr>
<tr>
<td>RANS</td>
<td>23,000(0.05)</td>
<td>50</td>
</tr>
</tbody>
</table>

- **Pitching condition**
  - Pitching center: 25% of chord
  - AoA: \(\alpha = \alpha_m + \alpha_0 \sin(\omega t)\)
    - Mean AoA: \(\alpha_m = 2.89\) [deg.]
    - Amplitude: \(\alpha_0 = 2.41\) [deg.]
    - Non-dimensional frequency: \(k = 0.0808\)

\[
k = \frac{\omega c}{2U_\infty} \quad \omega : \text{frequency} \quad c : \text{chord} \quad U_\infty : \text{free stream velocity}
\]
Results

$C_n - \alpha$ hysteresis loop

Mach contours (RANS)
Flutter Computation Using Fluid-Structure Interaction Code

- Flutter prediction for AGARD445.6 weakened wing
  - Compared with Yates’s experiment
Numerical Methods

- **Fluid analysis**
  - Governing equations: 3D Euler/RANS equations
  - Time integration: BDF2 (implicit)

- **Structure analysis**
  - Governing equation: Equation of motion using modal analysis
  - Mode analysis: 1st – 5th mode
  - Modal damping ratio: 0.02
  - Time integration: BDF2 (implicit)

- **Grid deformation**
  - Interpolation method using function weighted by inverse distance
AGARD445.6 Wing Structure Model

- **Wing size**
  - Root chord: 0.558 [m]
  - Span: 0.762 [m]
  - Aspect ratio: 1.65
  - Taper ratio: 0.66
  - Sweepback: 45 [deg.]
  - Airfoil: NACA65A004

- **Yates’s model**

<table>
<thead>
<tr>
<th>Mode</th>
<th>1st (bend)</th>
<th>2nd (torsion)</th>
<th>3rd (bend)</th>
<th>4th (torsion)</th>
<th>5th (bend)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eigen frequency [Hz]</td>
<td>Computational data (Yates)</td>
<td>9.6</td>
<td>38.2</td>
<td>48.3</td>
<td>91.5</td>
</tr>
<tr>
<td></td>
<td>Experimental data</td>
<td>9.6</td>
<td>38.1</td>
<td>50.7</td>
<td>98.5</td>
</tr>
</tbody>
</table>

Computational Grids

- **Euler**
  - Tetrahedrons: 190,436
  - Computational domain: 30 MAC

- **RANS**
  - Tetrahedrons: 178,278
  - Prisms: 310,464
  - Computational domain: 30 MAC
  - Off wall spacing: $2.4 \times 10^{-5}$ ($y^+ \leq 2$)
Computational Conditions

- **Free stream condition**
  - Mach number: 0.499, 0.678, 0.901, 0.960, 1.072, 1.141
  - AoA: 0.0 [deg.]

- **Initial condition**
  - Steady flow field solution
  - Tiny oscillation assumed in the 1st bending mode

- **Criteria for ending inner iteration**
  - $\Delta \rho < 10^{-7}$

- **CFL number, $\Delta t$, inner iteration**

<table>
<thead>
<tr>
<th></th>
<th>CFL ($\Delta t$)</th>
<th>Inner iteration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Euler</td>
<td>50 (0.0075)</td>
<td>8</td>
</tr>
<tr>
<td>RANS</td>
<td>400,000 (0.05)</td>
<td>20</td>
</tr>
</tbody>
</table>
Comparison of Flutter boundary

Flutter Speed Index (FSI)

\[ \text{FSI} = \frac{U_\infty}{b_s \omega_\alpha \sqrt{\mu}} \]

\[ \bar{\mu} = \frac{\bar{m}}{\rho_\infty v} \]

- \( U_\infty \): Free stream velocity
- \( b_s \): Half root chord
- \( \omega_\alpha \): Eigen frequency (1st torsion)
- \( \bar{\mu} \): Mass ratio
- \( \bar{m} \): Wing model mass
- \( \rho_\infty \): Free stream density
- \( v \): Truncated cone volume

Transonic dip
Distribution of $C_p$ on wing surface

**M=0.678**

**M=0.960**

**M=1.141**

Euler

RANS
Distribution of $C_p$ on several cross sections

- More dissipative shock wave in RANS
- Large Peak difference of negative $C_p$ at supersonic
Summary

- SV code is successfully extended to include:
  - ALE formulation
  - Unstructured hybrid meshes

- Code validation study for flowfield over NACA0012 airfoil in pitching motion
  - $C_n$ hysteresis loop is successfully reproduced when viscous effect is taken into account

- Fluid-structure interaction code is developed to consider AGARD445.6 weakened wing
  - Flutter boundary is reproduced for subsonic cases
  - Transonic dip phenomenon is well reproduced
  - Consideration of viscous effect obviously improves flutter boundary prediction at supersonic freestream, though some distinctions are yet remained
Future Works

- Further study for AGARD445.6 wing flutter at supersonic freestream
  - Is RANS simulation adequate for quantitative prediction?
  - Do we need to employ LES or DES?
  - Is consideration of boundary layer transition necessary?

- Examine several aeroelastic problems chosen from AIAA Aeroelastic Prediction Workshop for improving numerical methods

- Consideration of wing flutter with engines mounted on wing