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Wing Flutter Computation Using Modified Spectral Volume Method

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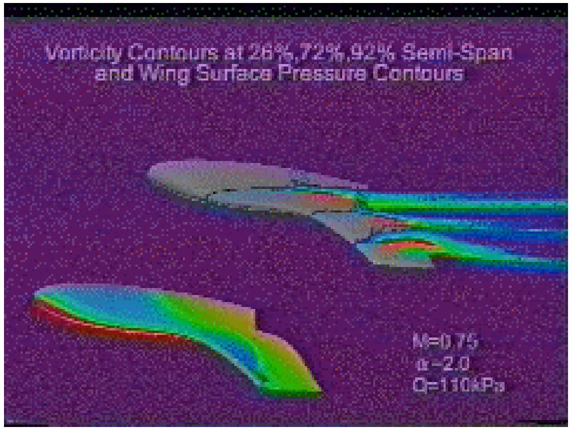
Outline

- 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

Numerical flutter analysis by JAXA



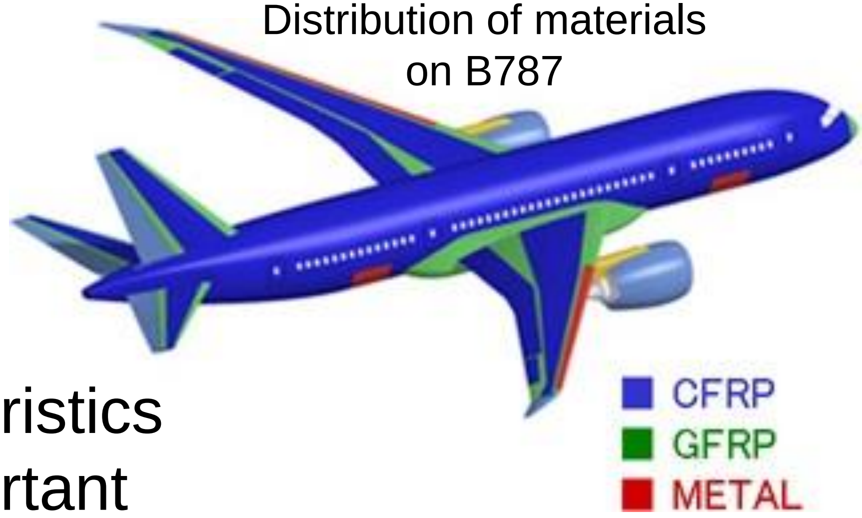
http://www.aero.jaxa.jp/reseach/kitai/ki-kuuriki.html

using composite materials

↓

stiffness decreases

Distribution of materials on B787



Examination of flutter characteristics is getting more and more important

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

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

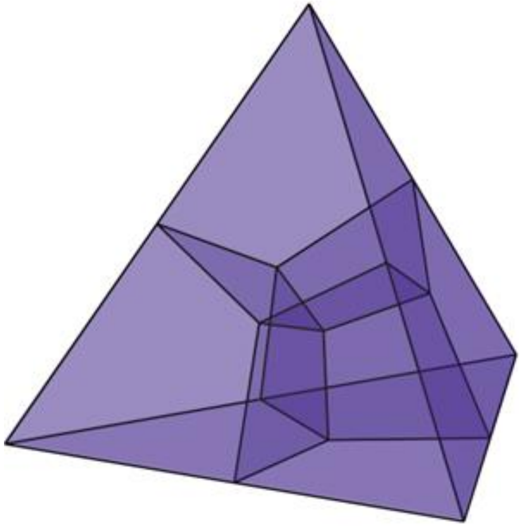
Conventional Spectral Volume Method

- ➢ Finite volume method
- ➢ High order unstructured grid method

Tetrahedral cell（= Spectral Volume（SV））

Further subdivided

4 hexahedral cells（= Control Volume（CV））



Tetrahedron
4DOFs

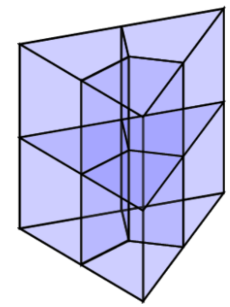
- Governing equations are solved in each CV
- Distribution of variables in SV is written by high order polynomial consists of 4 CV cell average values

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

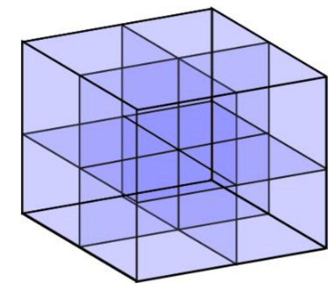
Shape function : $L_j(\xi,\eta,\zeta) = c_j^1\xi + c_j^2\eta + c_j^3\zeta + c_j^4$

Modified SV Method for Flutter Analysis

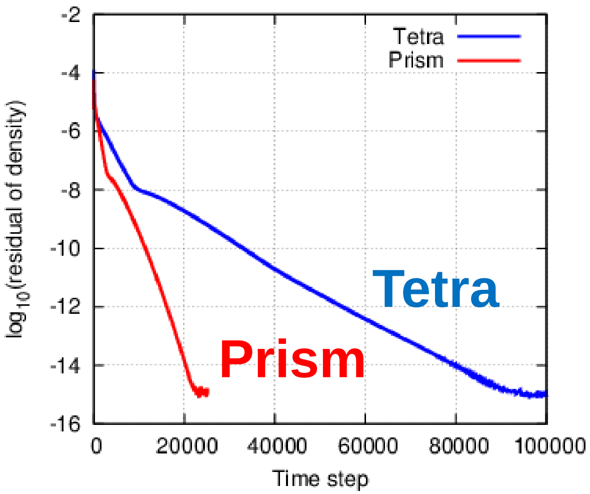
- Arbitrary Lagrangian-Eulerian（ALE） formulation for moving grid
- Extended to utilize **hybrid** unstructured meshes
  - Conventional SV utilizes **only tetrahedral cells（4DOFs）**
  - Although number of DOFs is increased in each cell other than tetrahedral cells, the total number of computational cells 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



Prism
6DOFs



Hexahedron
8DOFs



Convergence histories for turbulent boundary layer over flat plate

Validation of Present Code on Moving Grid

- Unsteady flowfield over NACA0012 airfoil in pitching motion
  - Compared with Landon's experiment

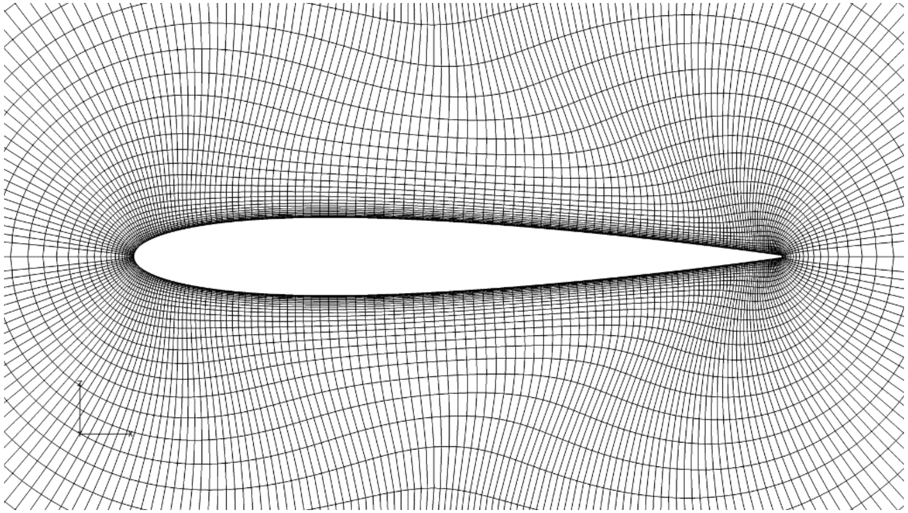
Numerical Methods

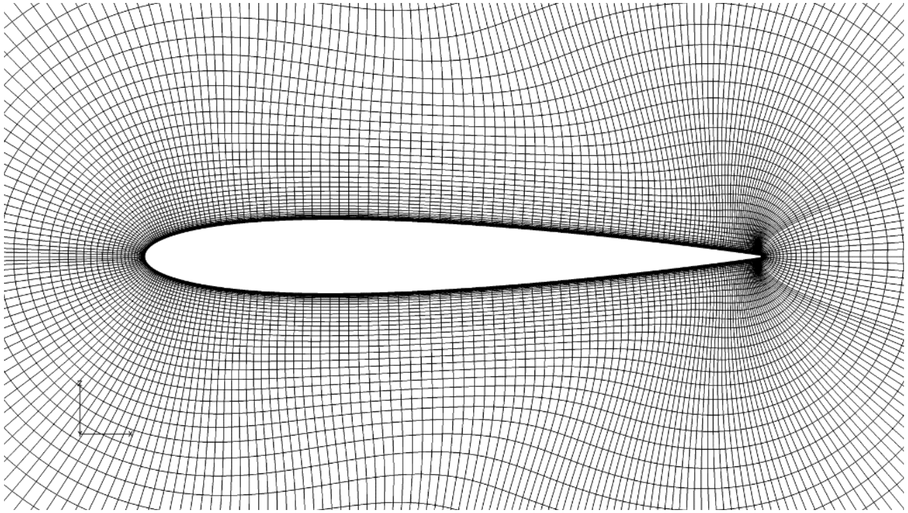
Governing equations	: 3D Euler/RANS equations
Spatial discretization	: 2nd order **modified** SV method
Numerical flux	: SLAU
Viscous term gradient	: BR2 method
Time integration	: 2nd order backward difference formula（BDF2）
Implicit method	: LU-SGS method with inner iteration
Turbulence model	: Spalart-Allmaras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

Computational Grids

- Euler
  - Hexahedrons：$19{,}720$
  - Computational domain：30 chord

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





Computational Conditions

- Free stream condition
  - Mach number：0.6
  - Reynolds number：4.8×10^6
- Criteria for ending inner iteration
  - $\Delta\rho < 10^{-7}$
- Δt, CFL, inner iterations

	CFL（Δt）	Inner iteration
Euler	300（0.05）	25
RANS	23,000（0.05）	50

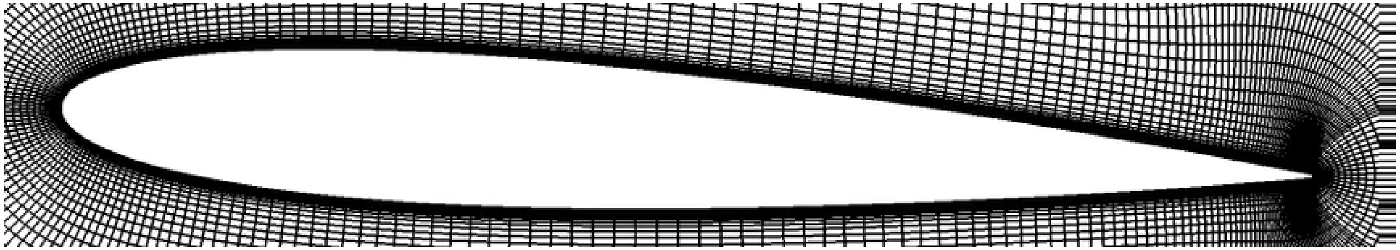
- Pitching condition
  - Pitching center：25% of chord
  - AoA： $\alpha = \alpha_m + \alpha_0 \sin(\omega t)$
    - Mean AoA： $\alpha_m = 2.89$[deg.]
    - Amplitude： $\alpha_0 = 2.41$[deg.]
    - Non-dimensional frequency：

$$k = 0.0808$$

$$k = \frac{\omega c}{2U_\infty}$$

ω :frequency c:chord

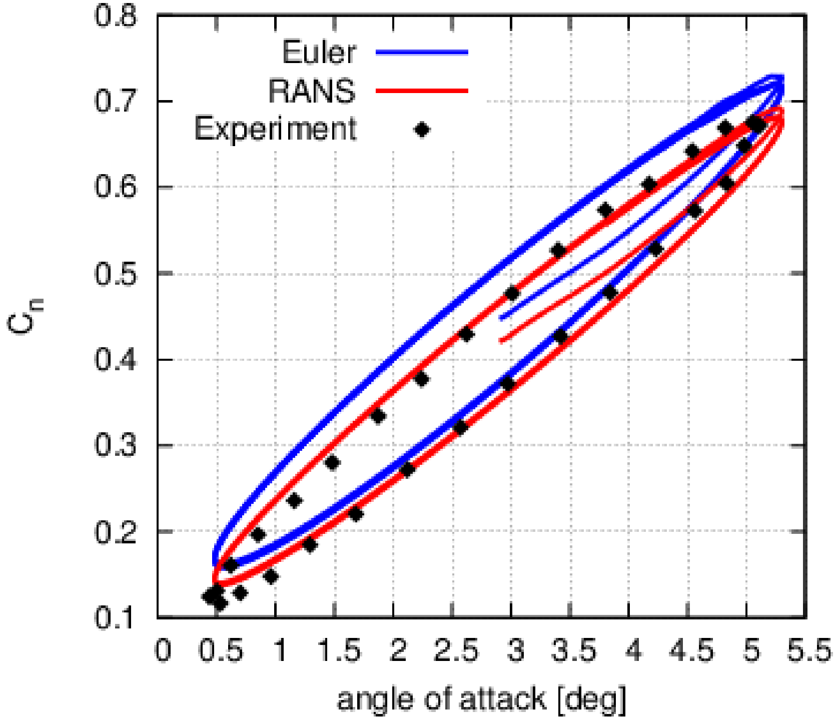
U_∞ :free stream velocity



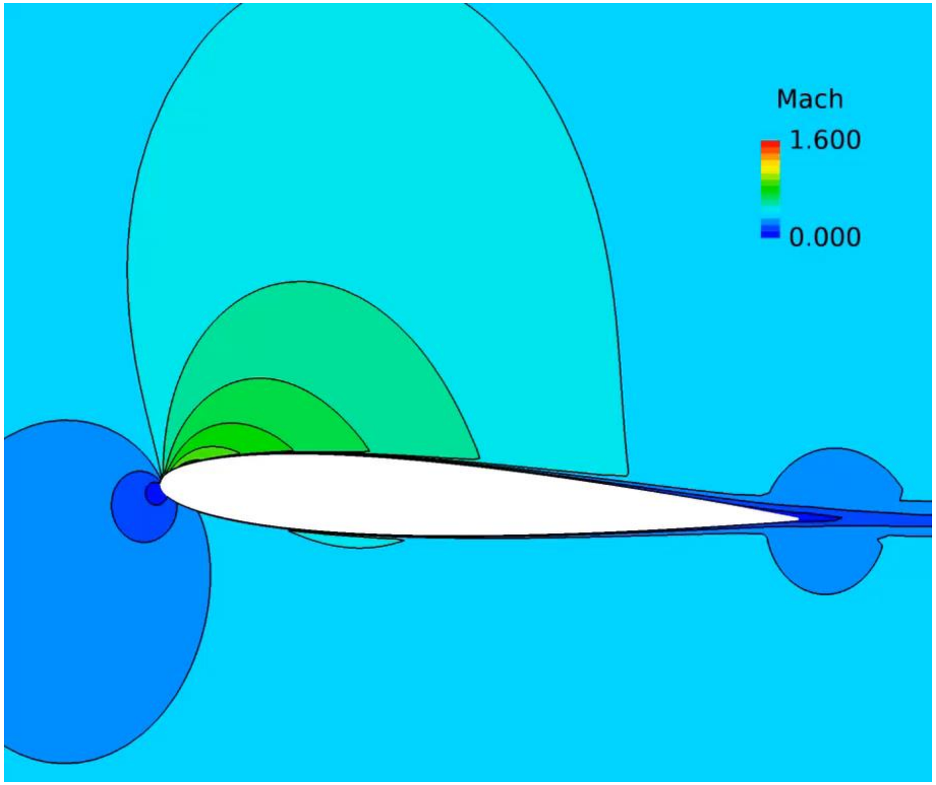
Pitching motion

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

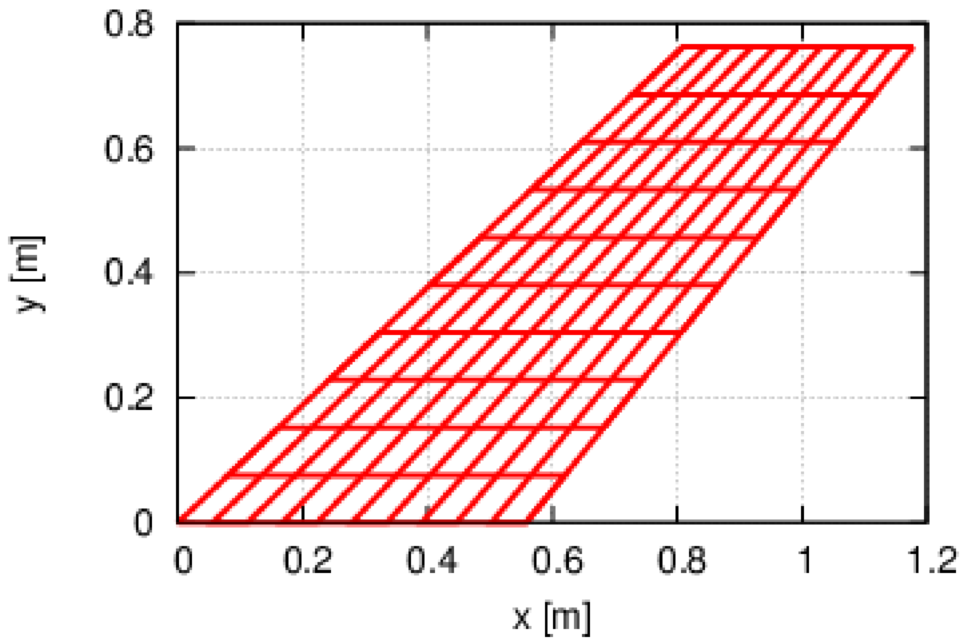
  Time integration :BDF2（implicit）

- **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



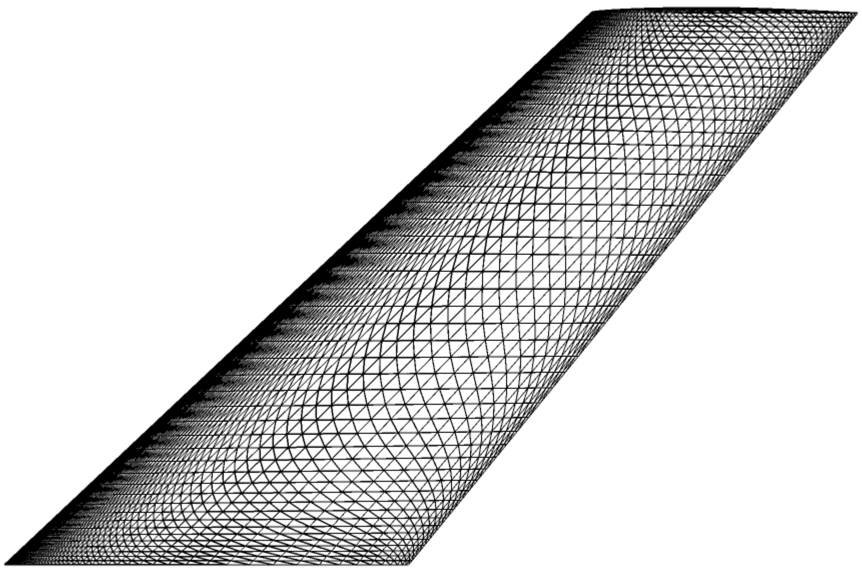
➢ Yates's model*

Mode		1st (bend)	2nd (torsion)	3rd (bend)	4th (torsion)	5th (bend)
Eigen frequency [Hz]	Computational data (Yates)	9.6	38.2	48.3	91.5	118.1
	Experimental data	9.6	38.1	50.7	98.5	-

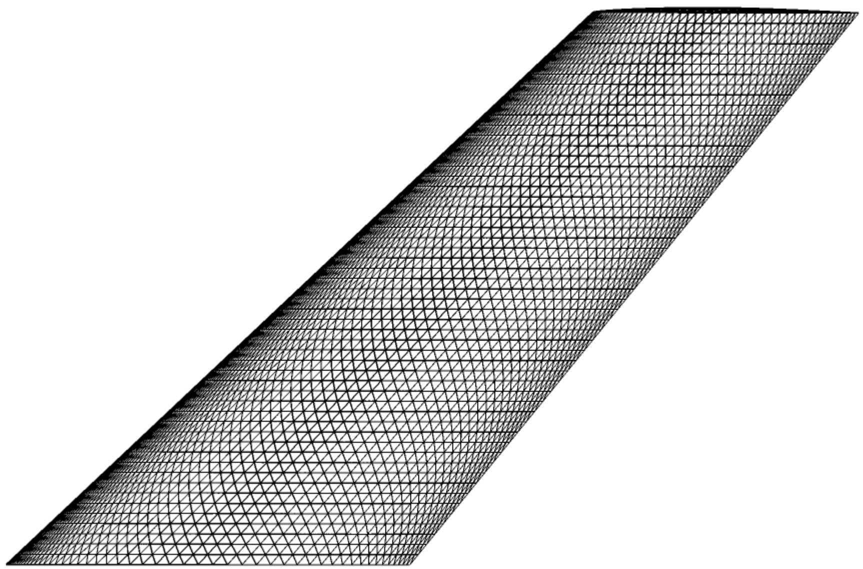
* E. Carson Yates Jr.,``AGARD Standard Aeloelastic Configuration for Dynamic Responce I-Wing 445.6", NASA TM 100492, 1987

Computational Grids

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



- RANS
  - Tetrahedrons：178,278
  - Prisms：310,464
  - Computational domain：30 MAC
  - Off wall spacing：2.4×10^{-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, Δt, inner iteration

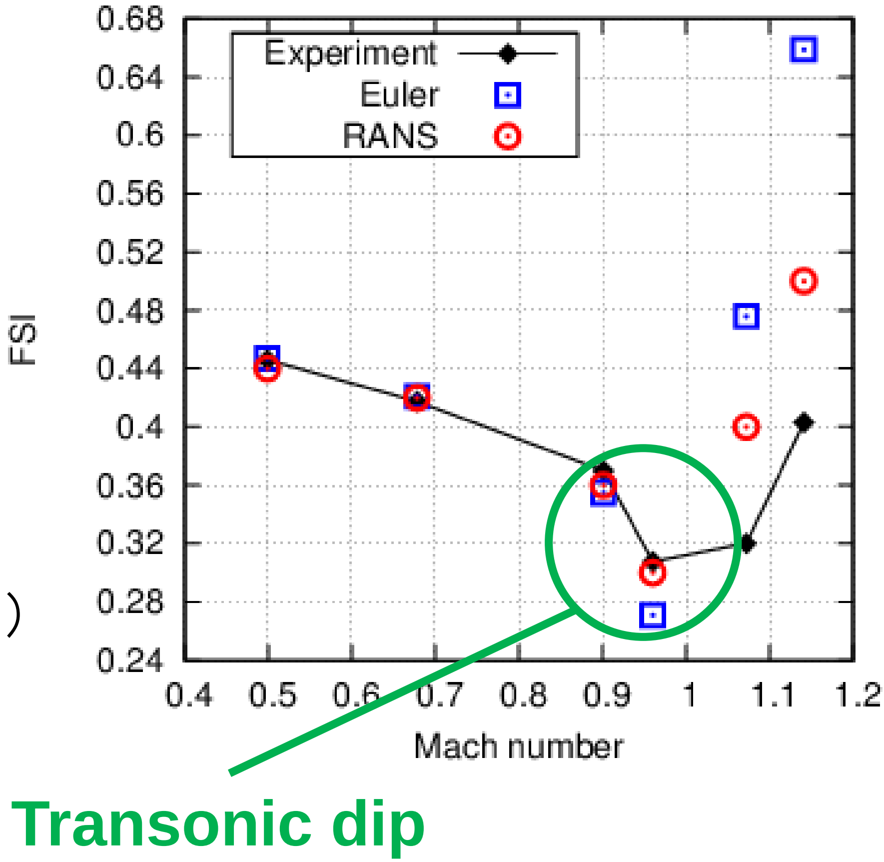
	CFL（Δt）	Inner iteration
Euler	50（0.0075）	8
RANS	400,000（0.05）	20

Comparison of Flutter boundary

Flutter Speed Index（FSI）

$$\mathrm{FSI} = \frac{U_\infty}{b_s \omega_\alpha \sqrt{\bar{\mu}}}$$

$$\bar{\mu} = \frac{\bar{m}}{\rho_\infty v}$$



U_∞ : Free stream velocity

b_s : Half root chord

ω_α : Eigen frequency（1st torsion）

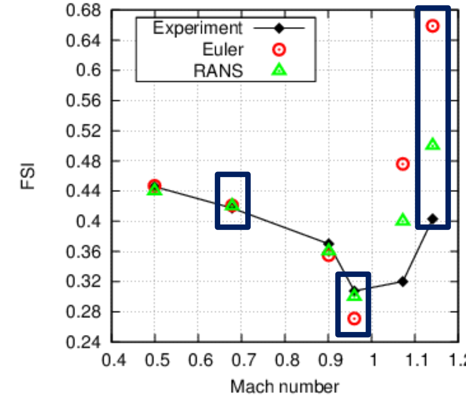
$\bar{\mu}$: mass ratio

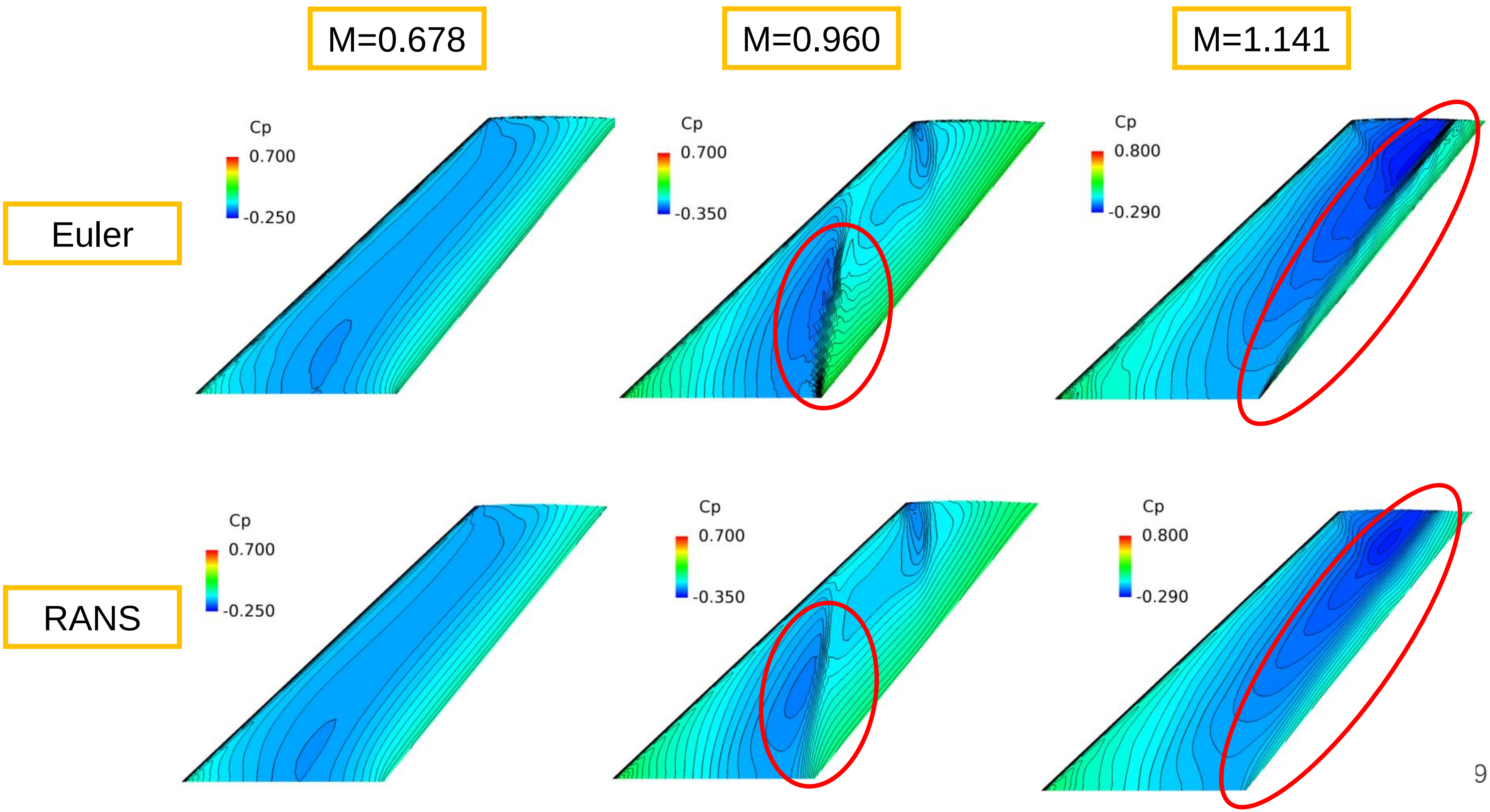
$\bar{m}$: Wing model mass

ρ_∞ : Free stream density

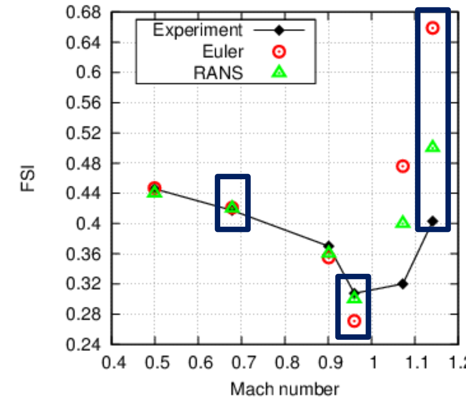
v : Truncated cone volume

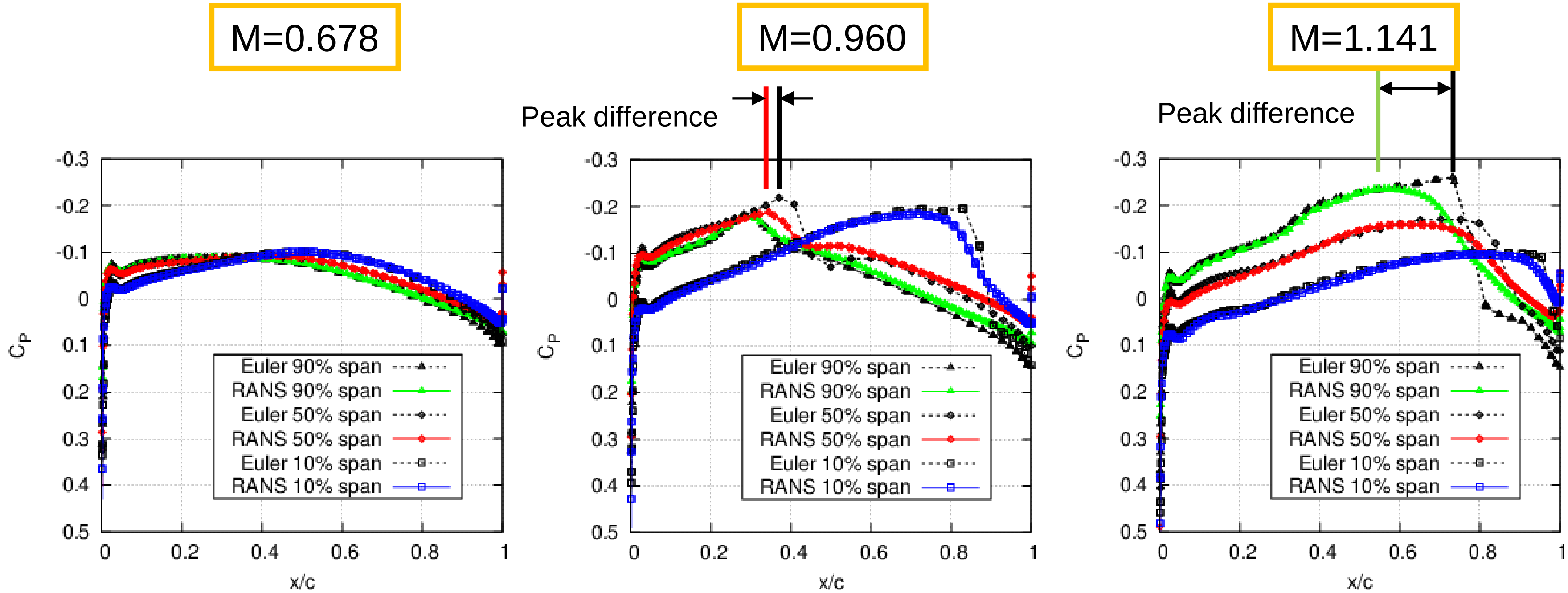
Distribution of C_p on wing surface





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