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Unsteady Flow Calculation Using Implicit Method on a Moving Unstructured Grid

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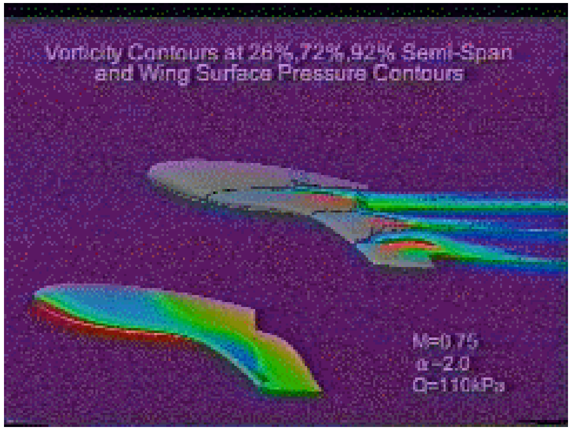
Outline

- Background
- Objective
- Spatial discretization method
- Validation of present code
    - NACA0012 airfoil pitching case
    - AGARD445.5 wing flutter case
- Summary
- Future works

Flutter

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

Numerical flutter analysis by JAXA



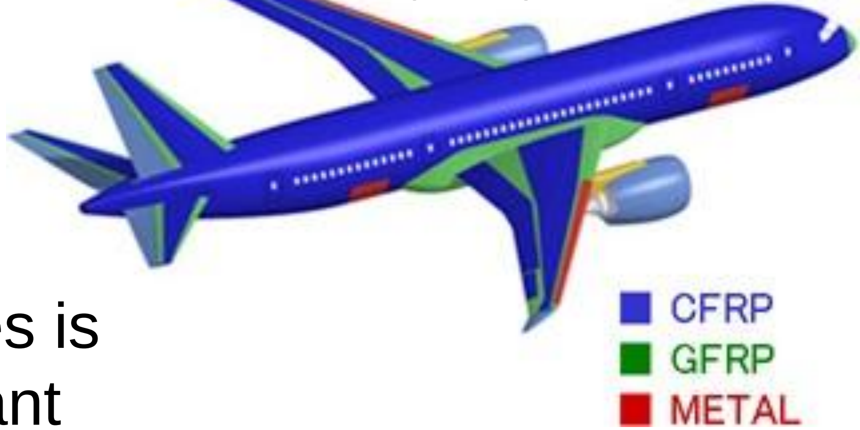
http://www.aero.jaxa.jp/reseach/kitai/ki-kuuriki.html

use composite materials

↓

stiffness decrease

Distribution of materials on B787



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

Examination of flutter properties is getting more and more important

Examination of Flutter Properties

- Wind tunnel test
- **Numerical analysis**

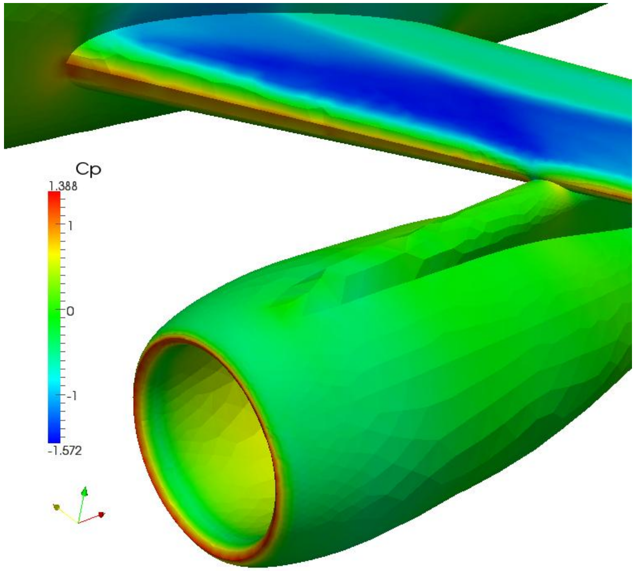
Analysis assuming **linear** aerodynamic force
- Insufficient result for shock wave
- Computational cost is lower

↓ Pursue performance by cutting extra margin of safety

Analysis assuming **non-linear** aerodynamic force
- Better result for shock wave
- Computational cost is higher
- Contribute to reduction of the number of tests

Objective

- ➢ Develop fluid-structure interaction code that can calculate flutter case on composite wing with engine-nacelles
  - CFD code development
    - FVM on moving grid
    - Unstructured grid method
    - Unsteady flow calculation
    - Implicit time integration
  - Code validation
    - NACA0012 airfoil pitching case
    - AGARD445.6 wing flutter case



http://adl.stanford.edu/docs/download/attachments/589829/DLR-F6_2.png?version=1&modificationDate=1323916413179&api=v2

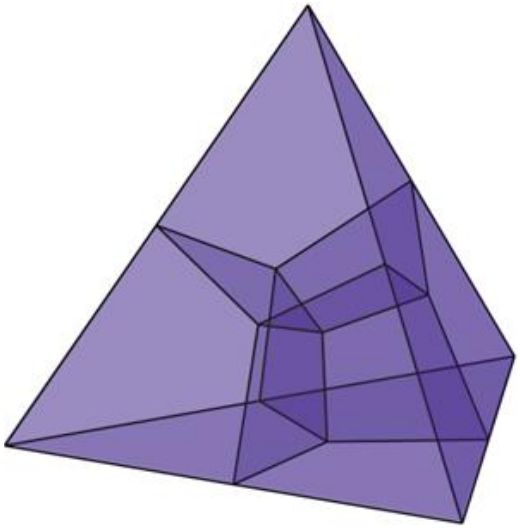
Spectral Volume Discretization

- 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 constructed by 4 CV cell average values

Validation of Moving Grid FVM Code

- NACA0012 airfoil pithing case
  - Compared with Landon’s experiment

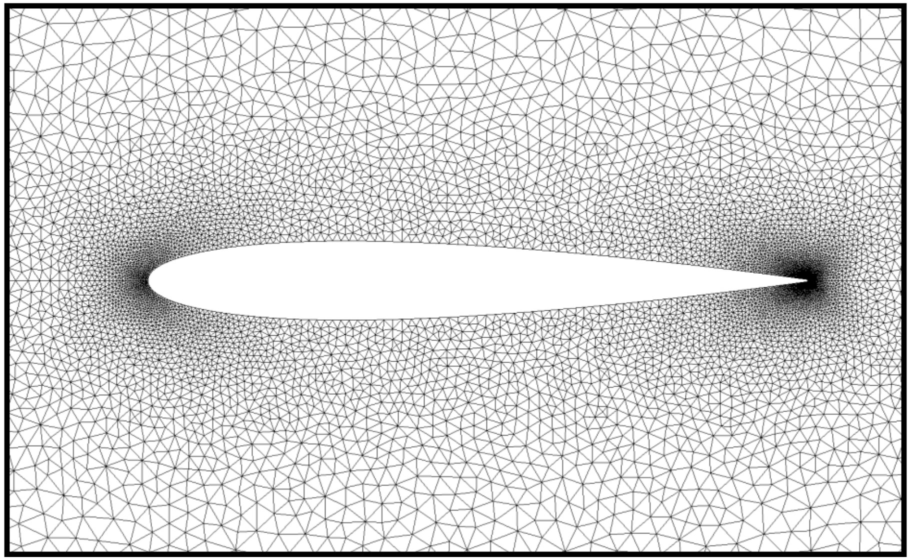
Numerical Methods

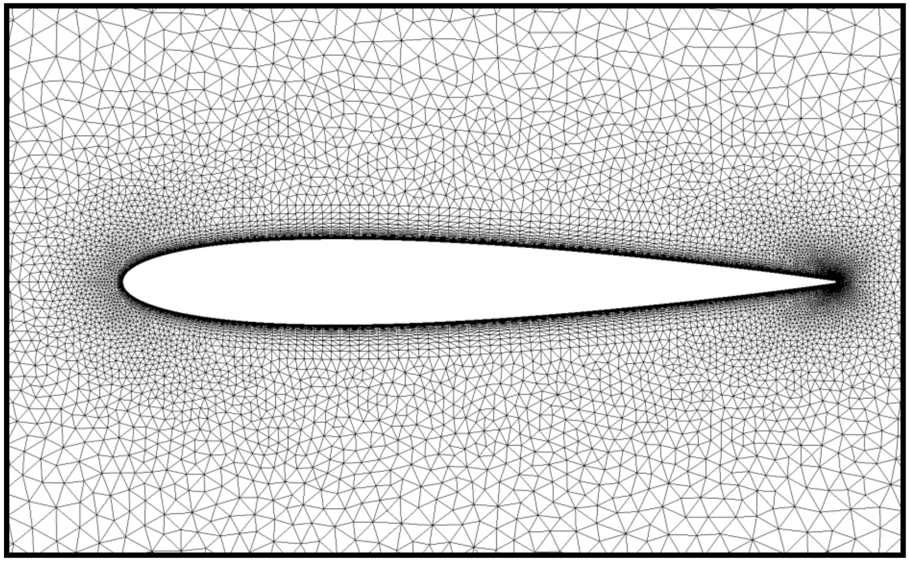
Governing equations	: 3D Euler/RANS equations
Spatial discretization	: 2nd order Spectral Volume（SV）method
Numerical flux	: SLAU, Rusanov（Implicit Jacobian）
Viscous term gradient	: BR2 method
Time integration	: 3rd order implicit Runge-Kutta method 3rd order explicit Runge-Kutta method
Implicit method	: LU-SGS method with inner iteration
Turbulent model	: Spalart-Allmaras model

Computational Grid

- Euler
  - Tetrahedra：72,006
  - Computational domain：30 chord

- RANS
  - Tetrahedra：99,486
  - Computational domain：30 chord
  - Off wall spacing： 5.5×10^{-6}
  （$y^{+}=1$ for $\mathrm{Re}=4.8\times10^{6}$）





Computational Conditions

- Free stream condition
  - Mach number : 0.6
  - Reynolds number : 4.8×10^6

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

- CFL number, Δt, inner iteration

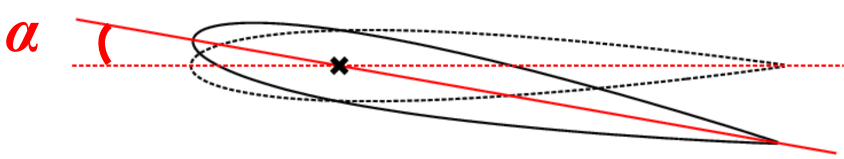
	CFL (Δt)	Inner iteration
Euler	150 (7.5×10^{-3})	10
RANS	750 (7.5×10^{-4})	16

- 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 : $k = 0.0808$

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

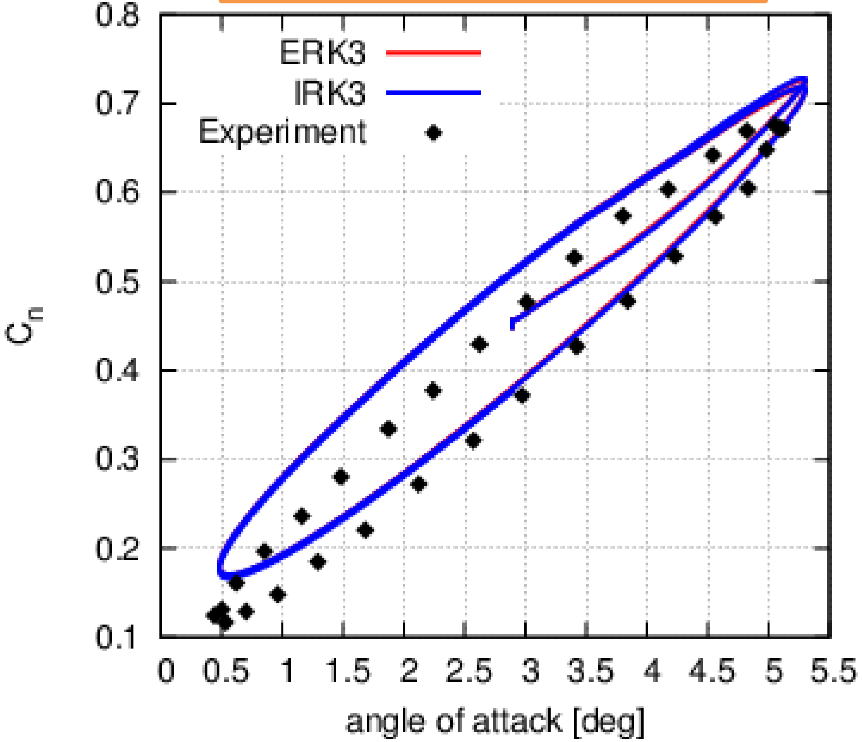
ω : frequency c : chord

U_∞ : free stream velocity

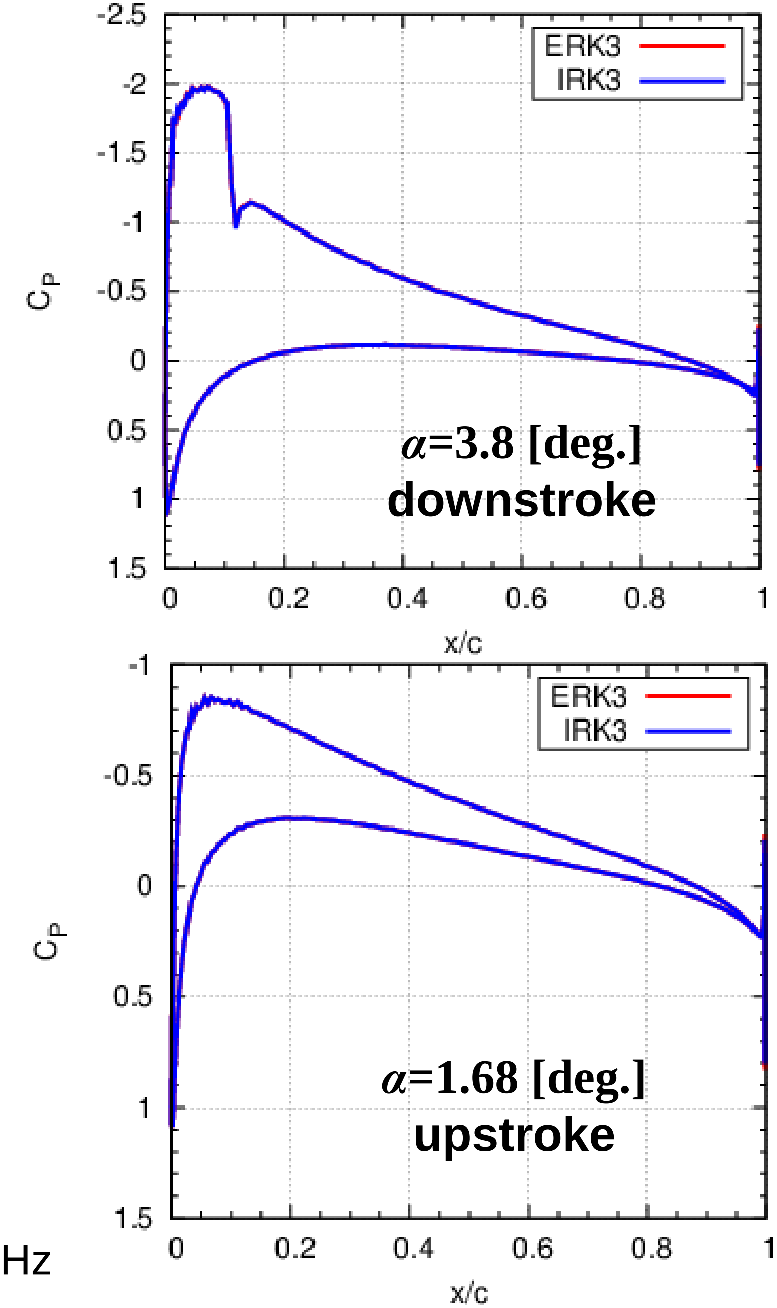


Explicit vs. Implicit（Euler）

$C_n - \alpha$ hysteresis loop



C_p distribution

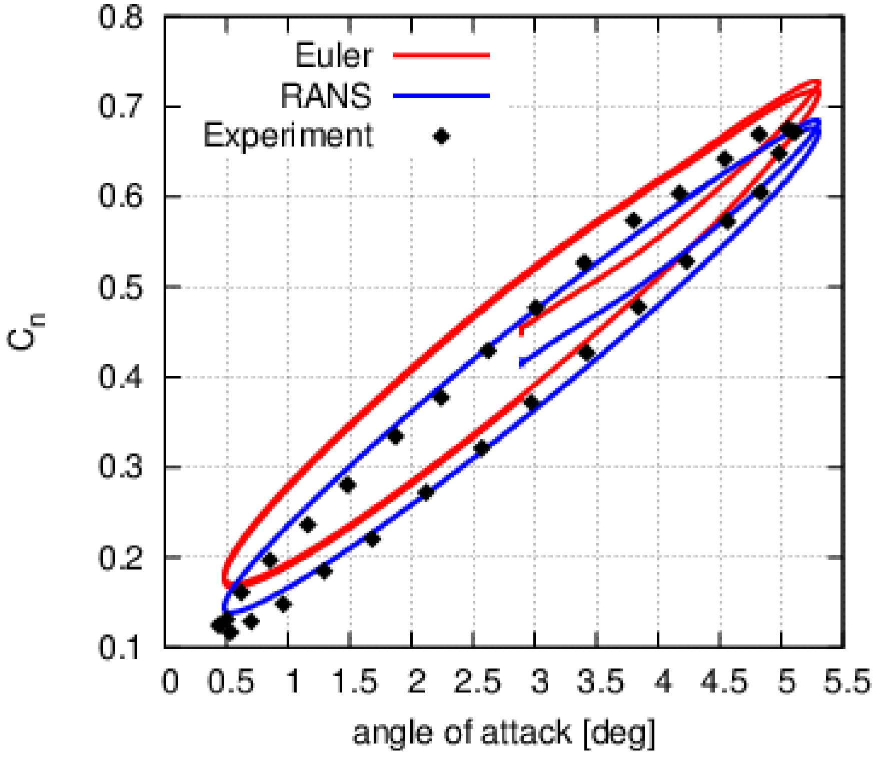


	Δt	CPU Time[/period]
ERK3	5.0×10^{-5}	7days
IRK3	7.5×10^{-3}	1day

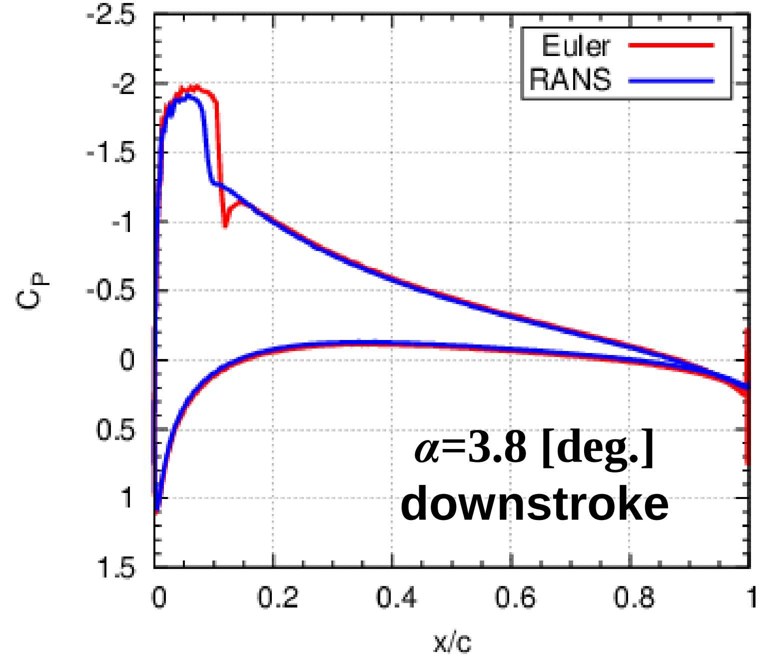
machine：Xeon E5-2687W 3.10GHz

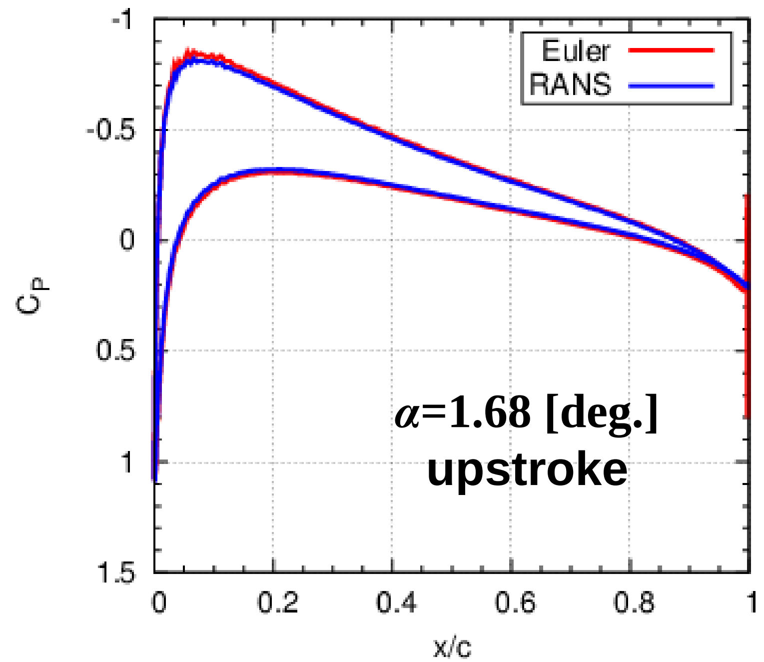
Euler vs. RANS（Implicit）

$C_n - \alpha$ hysteresis loop



C_p distribution





Validation of Fluid-Structure Interaction Code

- AGARD445.6 wing flutter case
  - Compared with Yates's experiment

Numerical Methods

- **Fluid analysis**

Governing equations	: 3D Euler equations
Time integration	: 2nd order Crank-Nicolson method

- **Structure analysis**

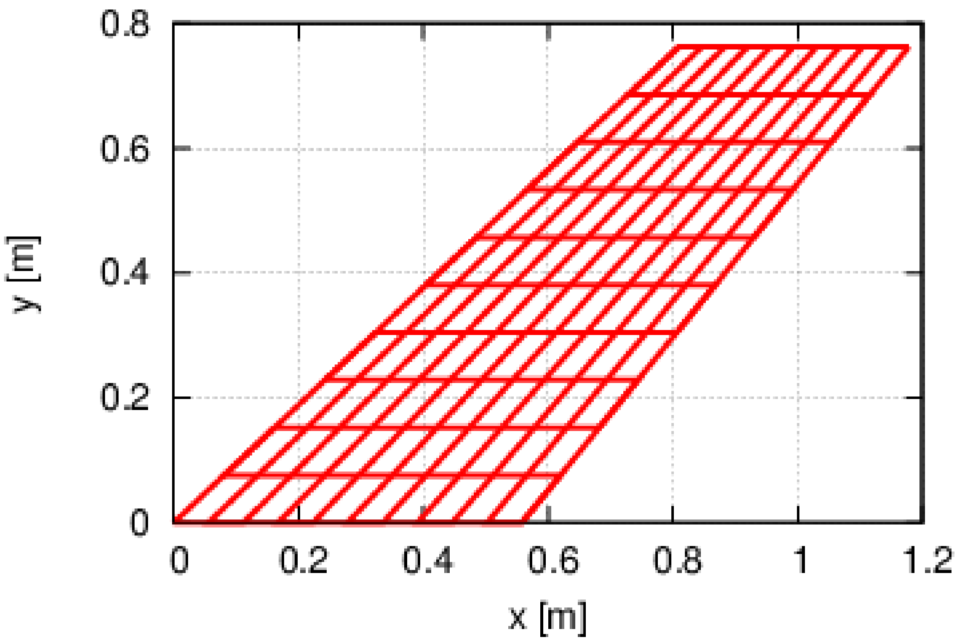
Governing equation	: Motion equation
Mode analysis	: 1st – 5th mode
Modal damping ratio	: 0.02
Time integration	: 2nd order backward difference

- **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



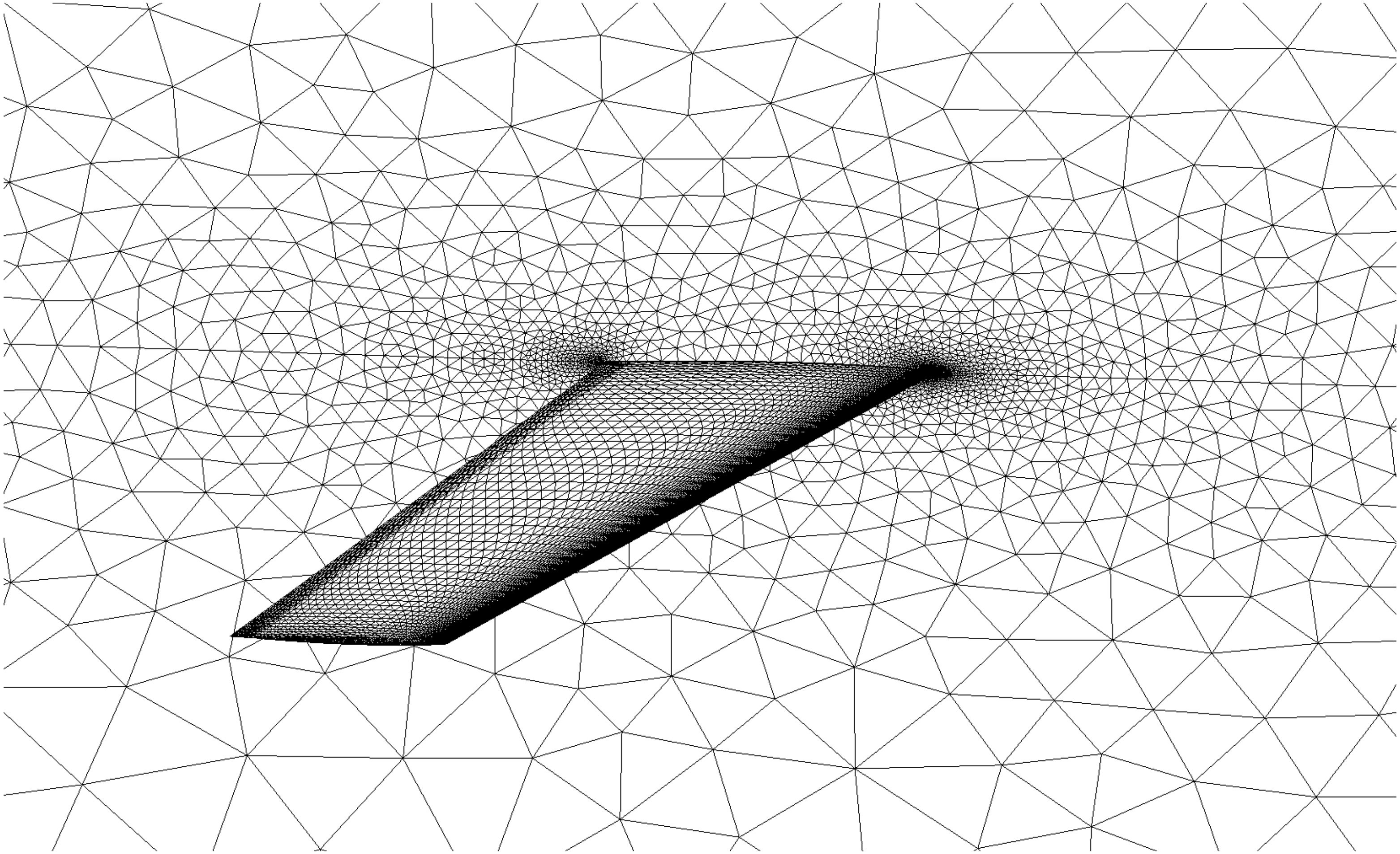
➢ Yates's model*

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 Grid

- Tetrahedra : 193,068
- Computational domain : 30 MAC



Computational Conditions

- Free stream condition
  - Mach number : 0.499, 0.678, 0.901, 0.960, 1.072, 1.141
  - AoA : 0.0 [deg.]
- Criteria for ending inner iteration
  - $\Delta Q < 10^{-7}$
- CFL number, Δt, inner iteration

	CFL（Δt）	Inner iteration
Euler	50（7.5×10^{-3}）	8

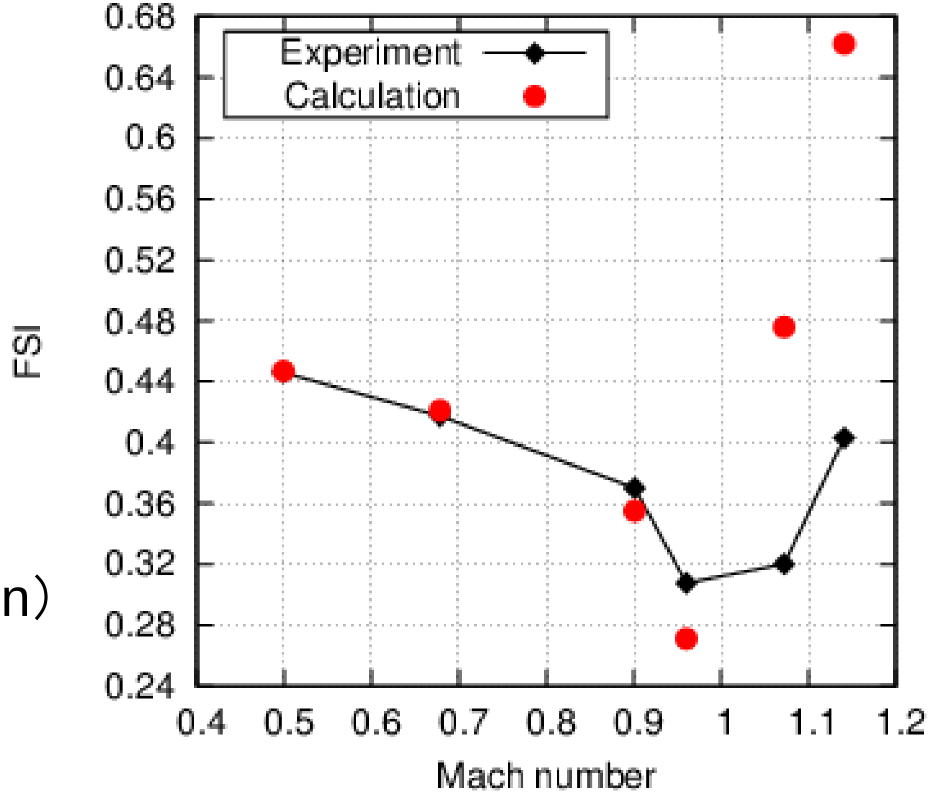
Flutter Boundary

Flutter Speed Index（FSI）

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

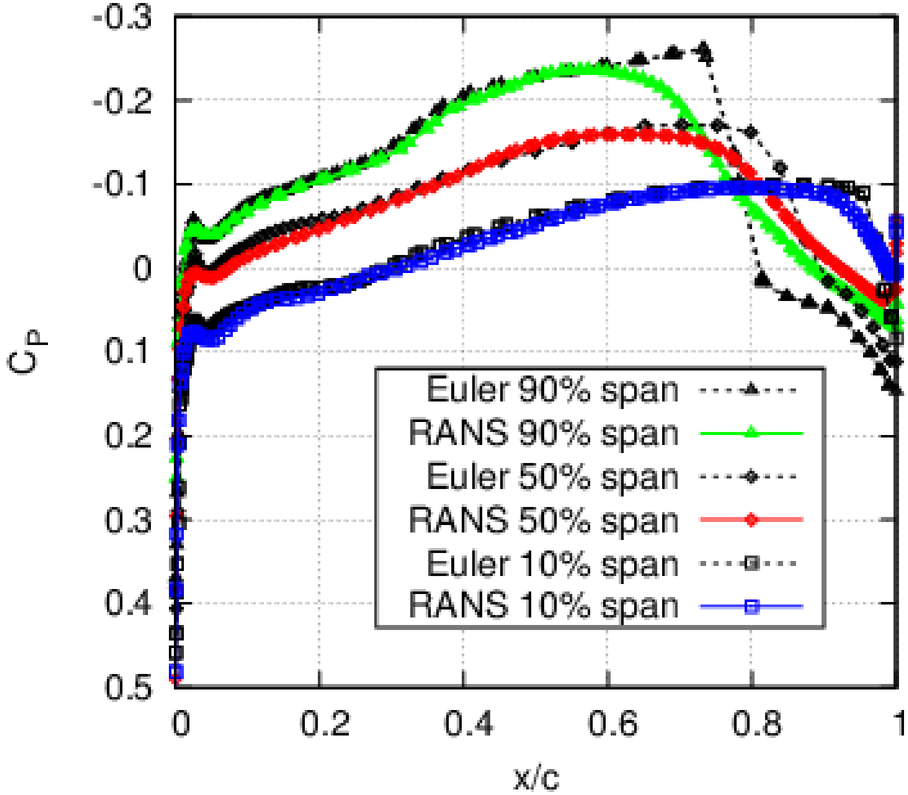
$$\bar{\mu} = \frac{\bar{m}}{\rho_\infty v}$$

U_∞ : Free stream velocity
b_s : Half root chord
ω_α : Eigen frequency（1st torsion）
$\bar{m}$: Wing model mass
ρ_∞ : Free stream density
v : Truncated cone volume

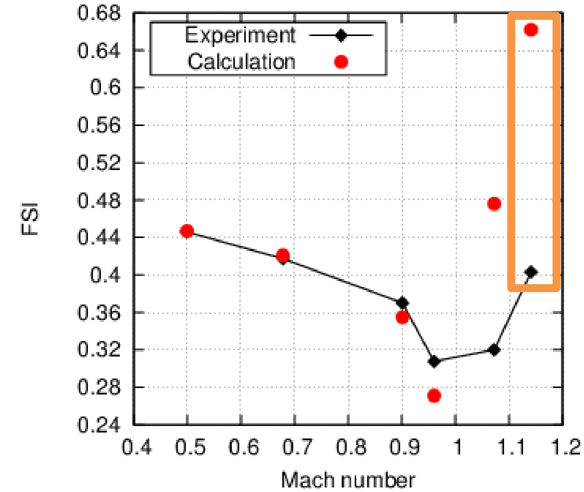


C_p Distribution（Euler vs. RANS）

Steady solution
（Mach number=1.141）



Flutter boundary（Euler）



Different distribution between Euler and RANS at shock wave

Summary

- CFD code on moving grid was developed
  - ✓ NACA0012 airfoil pitching case
  - C_n hysteresis loop was obtained
  - Computational cost by implicit method was 1/7 as compared with explicit method without getting worse result
  - Results came close to experimental data by considering viscosity

- Fluid structure interaction code was developed
  - ✓ AGARD445.6 wing flutter case
  - Good agreements with experimental data were obtained at subsonic
  - Unique transonic dip to non-linear phenomena was observed
  - Flutter boundary was overestimated at supersonic

Future Works

- AGARD445.6 wing flutter case（supersonic region）
  - Viscous flow analysis
  - Dense grid at trailing edge to capture shock wave
- Flutter analysis on composite wing with engine-nacelles