FUN3D v13.4 Training

Session 14: Dynamic Grid Simulations

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Session Scope

- What this will cover
  - How to set up and run time-accurate simulations on dynamic meshes
    - Nondimensionalization
    - Choosing the time step
    - Body / Mesh motion options
    - Input / Output
- What will not be covered
  - Specifics for overset and aeroelastic: covered in follow-on sessions
- What should you already be familiar with
  - Basic steady-state solver operation and control
  - Basic flow visualization

Introduction

- Background
  - Many of problems of interest involve moving or deforming geometries
  - Governing equations written in Arbitrary Lagrangian-Eulerian (ALE) form to account for grid speed
  - Nondimensionalization often more involved/confusing/critical
- Compatibility
  - Fully compatible for compressible/incompressible flows; mixed elements; 2D/3D
  - Not compatible with generic gas model
- Status
  - Compressible path with moving grids is exercised routinely; incompressible path much less so
  - 6-DOF option has had very limited testing / usage

Governing Equations

- Arbitrary Lagrangian-Eulerian (ALE) Formulation

$$\frac{\partial(\vec{Q}V)}{\partial t} = -\oint_{\partial V}\left(\overline{\overline{F}} - \vec{q}\vec{W}^T\right)\cdot\vec{n}dS - \oint_{\partial V}\overline{\overline{F}}_v\cdot\vec{n}dS = \vec{R} \qquad \vec{Q} = \frac{\oint_V \vec{q}\,dV}{V}$$

$\vec{W} =$ Arbitrary control surface velocity; Lagrangian if $\vec{W} = (u,v,w)^T$ (moves with fluid); Eulerian if $\vec{W} = 0$ (fixed in space)

- Discretize using N^th order backward differences in time, linearize $\vec{R}$ about time level n+1, and introduce a pseudotime term:

$$\left[\left(\frac{V^{n+1}}{\Delta\tau} + \frac{V^{n+1}\phi_{n+1}}{\Delta t}\right)\overline{\overline{I}} - \frac{\partial\vec{R}^{n+1,m}}{\partial\vec{Q}}\right]\Delta\vec{Q}^{n+1,m} = \vec{R}^{n+1,m} - \frac{V^{n+1}\phi_{n+1}}{\Delta t}\left(\vec{Q}^{n+1,m} - \vec{Q}^n\right) - \ldots + \vec{R}^{n+1}_{GCL}$$

$$= \overline{\vec{R}^{n+1,m}} + O(\Delta t^N)$$

- Physical time-level t^n ; Pseudo-time level τ^m
- Need to drive ***subiteration residual*** $\overline{\vec{R}^{n+1,m}} \to 0$ using pseudotime subiterations at each time step – more later – otherwise you have more error than the expected $O(\Delta t^N)$ truncation error

Mesh / Body Motion (1/2)

- Motion is triggered either by setting **`moving_grid = .true.`** in **`&global`** (**`fun3d.nml`**), or by the command line **`--moving_grid`**
- All dynamic-mesh simulations require some input data via an auxiliary namelist file: **`moving_body.input`**
- A body is defined as a user-specified collection of solid boundaries in grid
- Body motion options:
  - – Several built-in functions for rigid-body motion: translation and/or rotation with either constant velocity or periodic displacement
  - – Read a series of surface files – body can be either rigid or deforming
  - – Read a series of 4x4 transform matrices - rigid body
  - – 6 DOF via UAB/Kestrel library “libmo”
    - Limited distribution
    - Requires configuring with **`--with-sixdof=/path/to/6DOF`**
  - – Application-specific: mode-shape based aeroelasticity (linear structures); rotorcraft nonlinear beam

Mesh / Body Motion (2/4)

- Chose a mesh-motion option than can accommodate the desired body-motion option
- Mesh motion options:
  - Rigid - maximum 1 body containing all solid surfaces (unless overset)
  - Deforming - allows multiple bodies without overset; can be limited to relatively small displacements before mesh cells collapse
  - Combine rigid and/or deforming with overset for large displacements / multiple bodies
- Rigid mesh motion performed by application of 4x4 transform matrix to all points in the mesh - fast; positivity of cell volumes guaranteed to be maintained
  - Complex transforms can be built up from simple ones: matrix multiply
  - Allows parent-child motion (child follows parent but can have its own motion on top of that)

Mesh / Body Motion (3/4)

- Mesh deformation handled via solution of a linear elasticity PDE:

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

$$\lambda = \frac{E\upsilon}{(1+\upsilon)(1-2\upsilon)} \qquad \mu = \frac{E}{2(1+\upsilon)}$$

  – υ (Poisson's ratio) is fixed; E (Young's modulus)

  – Elasticity parameters are controlled by **`&elasticity_gmres`** (in the **`fun3d.nml`** file):

    - **`elasticity=1`** Young's modulus (1⇒ wall distance, 2 ⇒ cell volume)
    - **`elasticity_exponent=1.0`** Inverse power for Young's modulus
    - With default parameters, the Young's modulus will be:

E = 1 / slen**1.0

Mesh / Body Motion (4/4)

- Elasticity solved via GMRES method (preferred) or multicolor point solver
  - GMRES requires the SPARSKIT library:
    - Need to configure with **`--with-SPARSKIT=/path/to/SPARSKIT`**
- GMRES solver has default parameter settings, which can be adjusted in the namelist **`&elasticity_gmres`**:

```
ileft   nsearch nrestarts        tol
    1        50        10     1.e-06
```

  - You generally won't have to adjust these values
  - If negative volumes are generated, try:
    - Decreasing the convergence tolerance, **`tol`**
    - Increasing the number of iterations (**`nsearch`** `x` **`nrestarts`** for GMRES) to allow further convergence
    - Setting **`elasticity=2`**
    - Setting **`elasticity_exponent=2.0`**

Nondimensionalization of Motion Data (1/2)

- Recall: * indicates a dimensional variable, otherwise nondimensional
- Typical motion data we need to nondimensionalize: translational velocity, translational displacement, angular velocity, and oscillation frequency
- Angular or translational displacements / velocities are input into FUN3D as magnitude and direction
- Displacement input: angular in degrees; translational $\Delta\vec{x} = \Delta\vec{x}^* / (L^*_{ref} / L_{ref})$
- Translational velocity is nondimensionalized just like flow velocity:
  - U^* = translation speed of the vehicle (e.g., ft/s)
  - $U = U^* / a^*_{ref}$ (comp.; this is a Mach No.) $U = U^* / U^*_{ref}$ (incomp)
- Rotation rate:
  - Ω^* = body rotation rate (e.g. rad/s)
  - $\Omega = \Omega^* (L^*_{ref}/L_{ref}) / a^*_{ref}$ (comp) $\Omega = \Omega^* (L^*_{ref}/L_{ref}) / U^*_{ref}$ (incomp)
  - Other variants on specified rotation rate are possible, e.g., rotor tip speed, from which $\Omega^* = U^*_{tip} / R^*$

Nondimensionalization of Motion Data (2/2)

- Oscillation frequency of the physical problem can be specified in different forms
  - f^* = frequency (e.g., Hz)
  - ω^* = circular frequency (rad/s)
    $= 2\pi f^*$
  - k = reduced frequency, $k = ½\, L^*_{ref}\, \omega^* / U^*_{ref}$ (be careful of exact definition - sometimes a factor of ½ is not used)
- Built-in sinusoidal oscillation in FUN3D is defined as $\sin(2\pi f t + \delta)$ where the nondimensional frequency f and phase lag δ are user-specfied
- So the corresponding nondimensional frequency for FUN3D is
  - $f = f^* (L^*_{ref} / L_{ref}) / a^*_{ref}$ (comp) $f = f^* (L^*_{ref} / L_{ref}) / U^*_{ref}$ (incomp)
  - $f = \omega^* (L^*_{ref} / L_{ref}) / (2\pi a^*_{ref})$ $f = \omega^* (L^*_{ref} / L_{ref}) / (2\pi U^*_{ref})$
  - $f = k M^*_{ref} / (\pi L_{ref})$ $f = k / (\pi L_{ref})$

Overview of `moving_body.input`

- A body is defined as a collection of solid boundaries in the grid
- The specifics of body / mesh motion are set in one or more namelists that are put in a file called **`moving_body.input`** - this file *must* be provided when **`moving_grid`** is triggered (as a CLO or **`&global`** entry)
  - The **`&body_definitions`** namelist defines one or more bodies that move and is *always* needed in a dynamic-grid simulation
  - The **`&forced_motion`** namelist provides a limited means of defining basic translations and rotations as functions of time
  - The **`&motion_from_file`** namelist defines the motion of a rigid body from a sequence of 4x4 transform matrices
  - The **`&surface_motion_from_file`** namelist defines the motion of a rigid or deforming body from a time sequence of boundary surfaces
  - The **`&observer_motion`** namelist provides a means of generating boundary animation output from a non-stationary reference frame
- **`&body_definitions`** is required with **`moving_grid`** , others optional

Overview of `&body_definitions` Namelist

- Only most-used items shown here – see manual for complete list
- The **`&body_definitions`** namelist defines the bodies that move (defaults shown; most need changing)

```
&body_definitions                   ! below, b=body  i=boundary
  n_moving_bodies         = 0  ! how many bodies in motion
  body_name(b)            = '' ! must set unique name for each
  parent_name(b)          = '' ! child inherits motion of parent
  n_defining_boundary(b)= 0  ! how many boundaries define body
  defining_boundary(i,b)= 0  ! list of boundaries defining body
  motion_driver(b)        = 'none' ! mechanism driving body motion
  mesh_movement(b)        = 'static' ! specifies how mesh will move
/
```

- ***Caution***: boundary numbers must reflect any lumping applied at run time!
- All variables above except **`n_moving_bodies`** are set for each body
- The blank string(**`''`**) for **`parent_name`** => inertial frame

Overview of `&body_definitions` (cont.)

- Options for **`motion_driver`** (default: **`'none'`**)
  - **`'forced'`**
    - Built-in forcing functions for rigid-body motion, const. or periodic
  - **`'surface_file'`**
    - File with surface meshes at selected times; interpolates in between
  - **`'motion_file'`**
    - File with 4x4 transforms at selected times; “interpolates” in between
  - **`'6dof'`**
    - relies on calls to “libmo” functions
  - **`'aeroelastic'`**
    - modal aeroelastics
  - All the above require additional namelists to specify details; next slide outlines namelist required when **`motion_driver='forced'`**
- Options for **`mesh_movement`** (default: **`'static'`**)
  - **`'rigid'`, `'deform'`, `'rigid+deform'`**

Overview of `&forced_motion` Namelist

- Use **`&forced_motion`** namelist to specify a limited set of built-in motions

```
&forced_motion           ! below, index b=body#
 rotate(b)               ! how to rotate this body: 0 don't (default);
                         ! 1 constant rotation rate; 2 sinusoidal in time
 rotation_rate(b)        ! body rotation rate; used only if rotate = 1
 rotation_freq(b)        ! frequency of oscillation; use only if rotate = 2
 rotation_amplitude(b)   ! oscillation amp. (degrees); only if rotate=2
 rotation_vector_x(b)    ! x-comp. of unit vector along rotation axis
 rotation_vector_y(b)    ! y-comp. of unit vector along rotation axis
 rotation_vector_z(b)    ! z-comp. of unit vector along rotation axis
 rotation_origin_x(b)    ! x-coord. of rotation center (to fix axis)
 rotation_origin_y(b)    ! y-coord. of rotation center
 rotation_origin_z(b)    ! z-coord. of rotation center
/
```

- There are analogous inputs for translation (**`translation_rate`**, etc.)
- See manual for complete list
- Note: FUN3D's sinusoidal oscillation function (translation or rotation) has 2π built in, e.g sin(2π **`rotation_freq t`**)

Output Files

- In addition to the usual output files, for forced / 6-DOF motion there are 3 ASCII Tecplot files for each body
  - **`PositionBody_N.dat`** tracks linear (x,y,z) and angular (yaw, pitch, roll) displacement of the "CG" (rotation center)
  - **`VelocityBody_N.dat`** tracks linear (V_x,V_y,V_z) and angular ($\Omega_x, \Omega_y, \Omega_z$) velocity of the "CG" (rotation center)
  - **`AeroForceMomentBody_N.dat`** tracks force components (F_x,F_y, F_z) and moment components (M_x,M_y,M_x)
  - Data in all files are nondimensional by default (e.g. "forces" are actually force coefficients); **`moving_body.input`** file has option to supply dimensional reference values such that *this* data is output in dimensional form - see manual/website for details
  - Forces are by default given in the inertial reference system; **`moving_body.input`** file has option to output forces in the body-fixed system - see manual/website for details

Tutorial Case: Pitching Airfoil (1/9)

- Test case located in: tutorials/flow_unsteady_airfoil_pitching
  - **`run_tutorial.sh`** script starts with a 600 time step restart file, runs an additional 100 steps, and makes plots that follow
- Consider one of the well known AGARD pitching airfoil experiments, "Case 1"
  - Re_{c^*} = 4.8 million, M_{inf} = 0.6, chord = c* = 0.1m , chord-in-grid = 1.0
  - Reduced freq. k = 2 π f * / (U^*_{inf} / 0.5c*) = 0.0808, (f *= 50.32 Hz)
  - Angle of attack variation (exp): $\alpha = 2.89 + 2.41 \sin(2\pi f^* t^*)$ (deg)
- Setting the FUN3D data:
  - **`angle_of_attack = 2.89   rotation_amplitude = 2.41`**
  - Recall f = k M^*_{ref} / π from the 2nd nondimensionalization slide
  - **`rotation_freq`** = f = 0.0808 (0.6) / 3.14… = 0.01543166
  - So in this case we actually didn't have to use any dimensional data since the exp. frequency was given as a reduced (non dim.) frequency

Tutorial Case: Pitching Airfoil (2/9)

- Setting the FUN3D data (cont):
  - Time step: the motion has gone through one cycle of motion when $t = T$, so that

    $\sin(2\pi$ **`rotation_freq`** $T) = \sin(2\pi)$

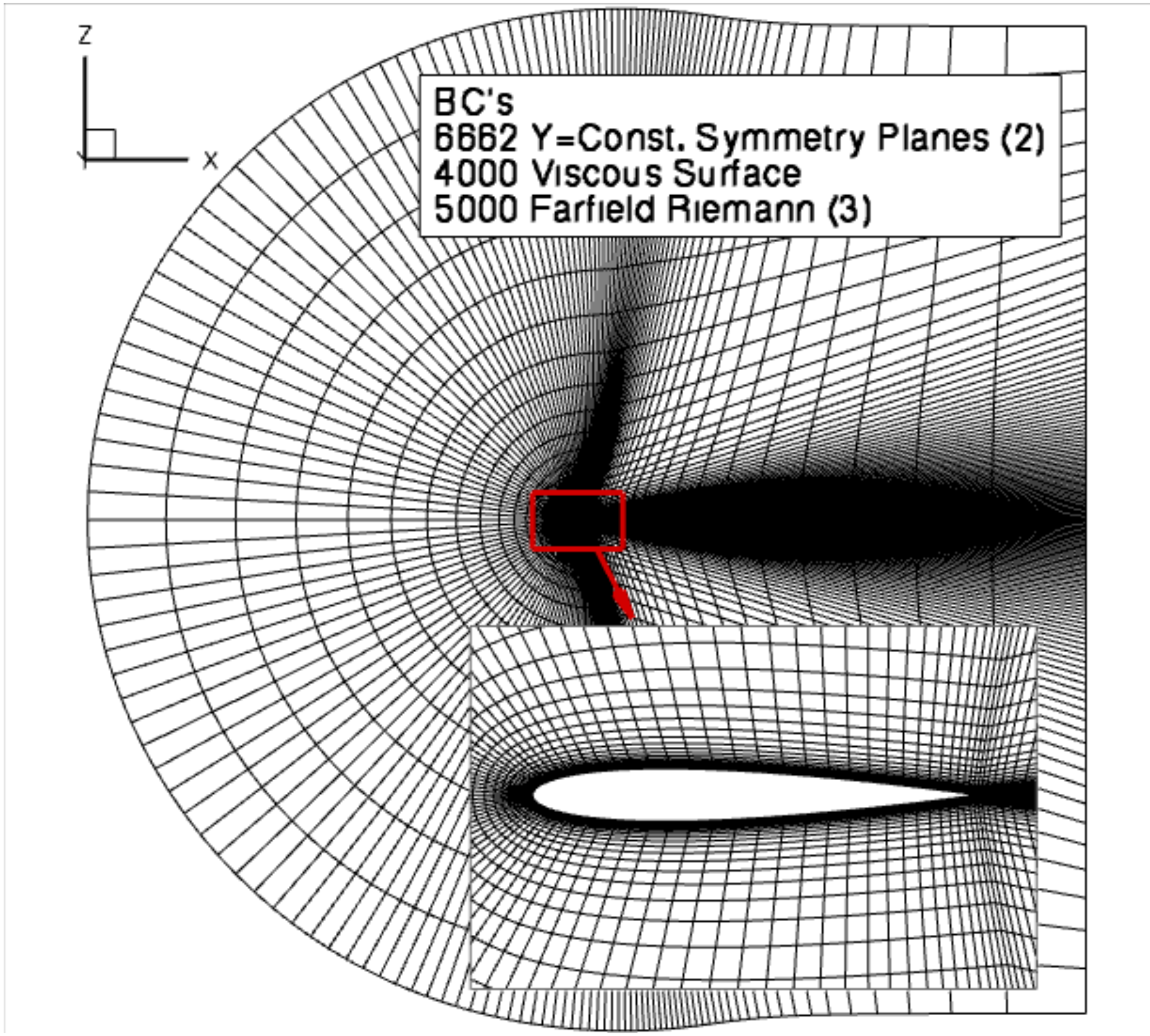
    $T = 1 /$ **`rotation_freq`** (this is our t_{chr})

    for N steps / cycle, $T = N \Delta t$ so

    $\Delta t = T / N = (1 /$**`rotation_freq`**$) / N$
  - Take 100 steps to resolve this frequency:

    $\Delta t = (1 / 0.01543166) / 100 = 0.64801842$
  - Alternatively, could use $t_{chr} = (1/ f^*) a^*_{inf} (L_{ref}/L^*_{ref})$, with $f^* = 50.32$ Hz, and assume value for a^*_{inf}

Tutorial Case: Pitching Airfoil (3/9)



Tutorial Case: Pitching Airfoil (4/9)

- Relevant **`fun3d.nml`** data

```
&global
   moving_grid = .true.
/
&nonlinear_solver_parameters
   temporal_err_control = .true.          ! Turn on
   temporal_err_floor   = 0.1             ! Exit 1 order below estimate
   time_accuracy        = "2ndorderOPT"   ! Our Workhorse Scheme
   time_step_nondim     = 0.64801842      ! 100 steps/pitch cycle
   subiterations        = 30
   schedule_cfl         = 50.00 50.00     ! constant cfl each step
   schedule_cflturb     = 30.00 30.00
/
```

- Relevant **`moving_grid.input`** data

```
&body_definitions
  n_moving_bodies      =  1,         ! number of bodies
  body_name(1)         = 'airfoil',  ! name must be in quotes
  n_defining_bndry(1)  =  1,         ! one boundary defines the airfoil
  defining_bndry(1,1)  =  5,         ! (boundary, body)
  motion_driver(1)     = 'forced'
  mesh_movement(1)     = 'rigid',
/
```

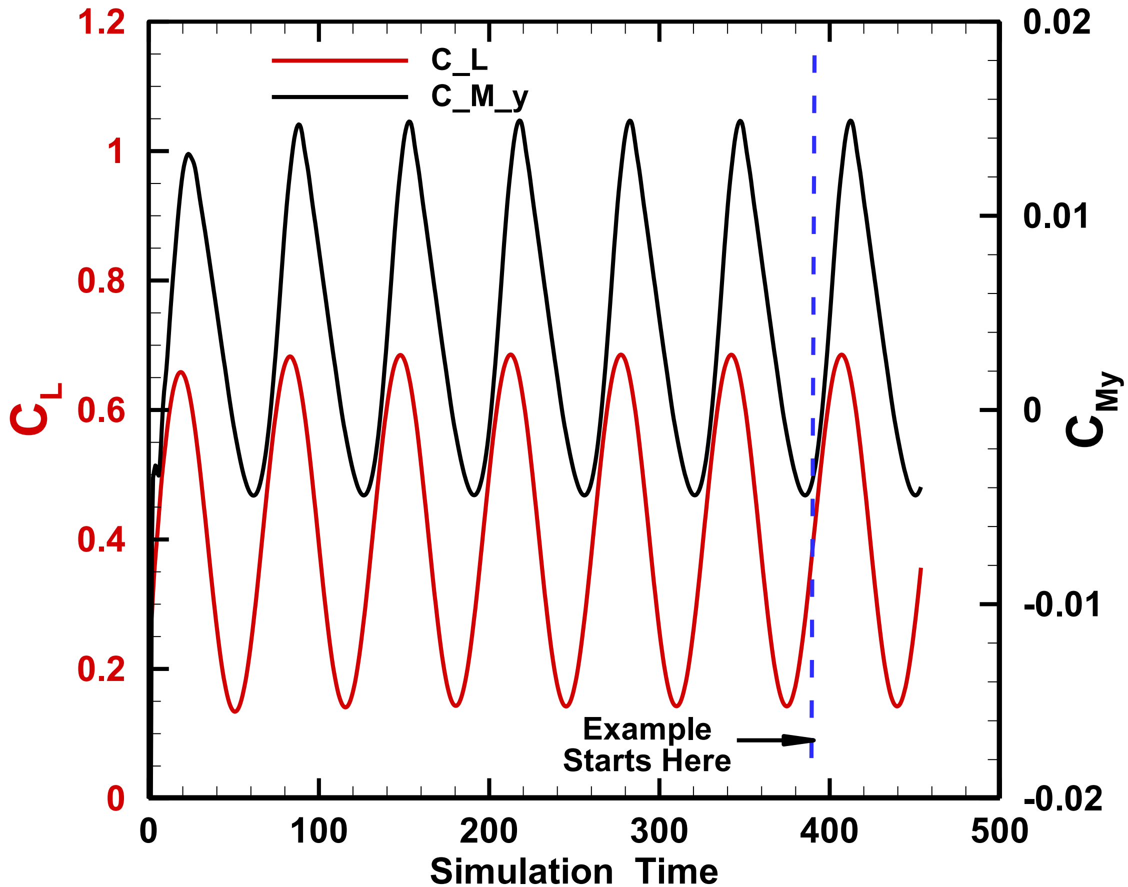
Tutorial Case: Pitching Airfoil (5/9)

- Relevant **`moving_grid.input`** data (cont)

```
&forced_motion
  rotate(1)             = 2,          ! type: sinusoidal
  rotation_freq(1)      = 0.01543166, ! reduced rotation frequency
  rotation_amplitude(1) = 2.41,       ! pitching amplitude
  rotation_origin_x(1)  = 0.25,       ! x-coordinate of rotation origin
  rotation_origin_y(1)  = 0.0,        ! y-coordinate of rotation origin
  rotation_origin_z(1)  = 0.0,        ! z-coordinate of rotation origin
  rotation_vector_x(1)  = 0.0,        ! unit vector x-component along
                                      ! rotation axis
  rotation_vector_y(1)  = 1.0,        ! unit vector y-component along
                                      ! rotation axis
  rotation_vector_z(1)  = 0.0,        ! unit vector z-component along
                                      ! rotation axis
/
```

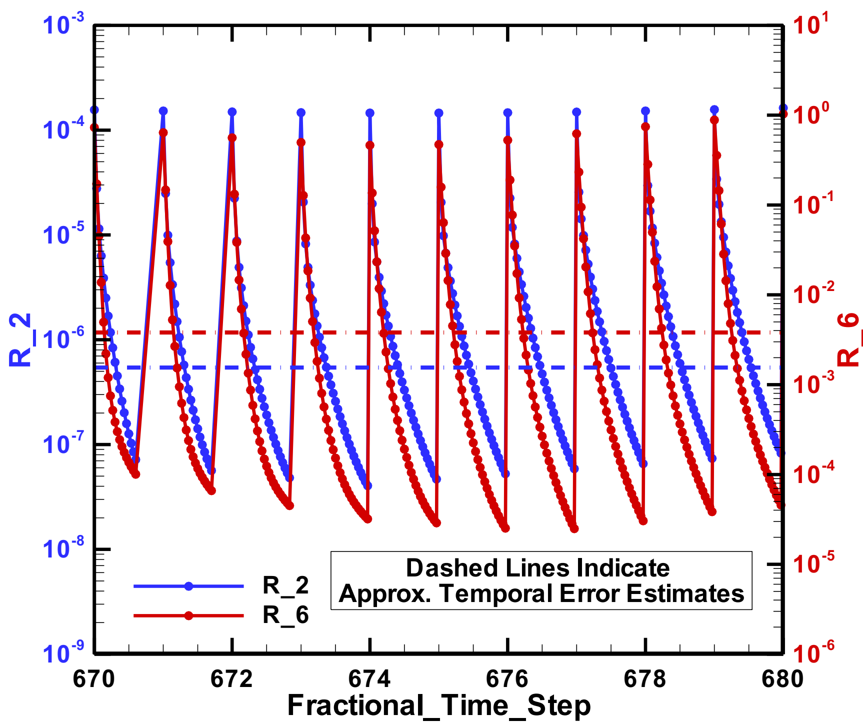
Tutorial Case: Pitching Airfoil (6/9)

Time History
(time_history.lay)

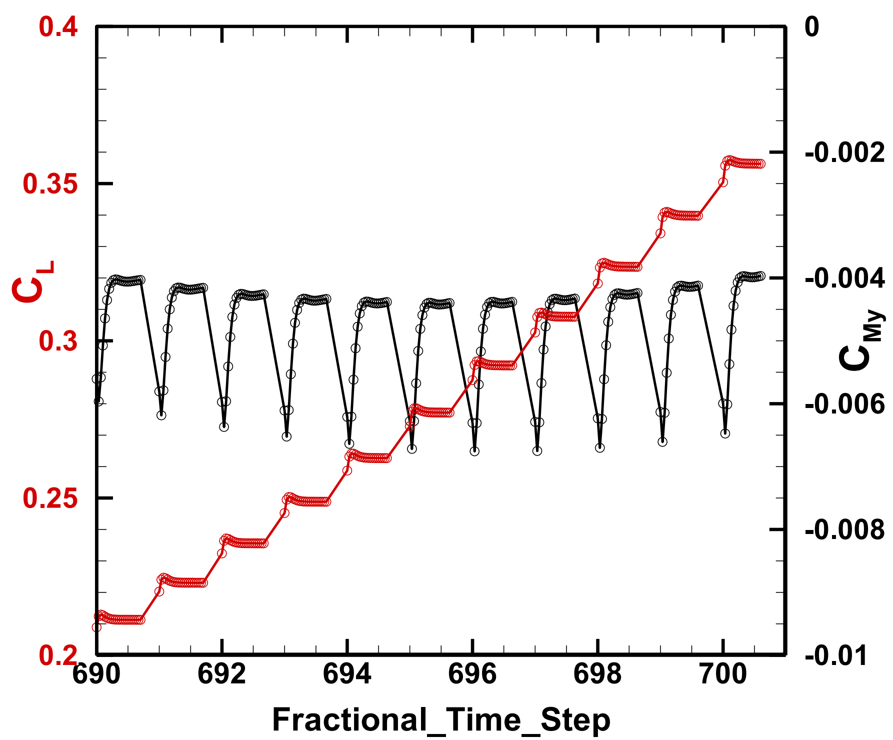


Tutorial Case: Pitching Airfoil (7/9)

Subiteration Residuals, Final 10 Steps
(mean flow just misses tolerance)
(subit_history.lay)

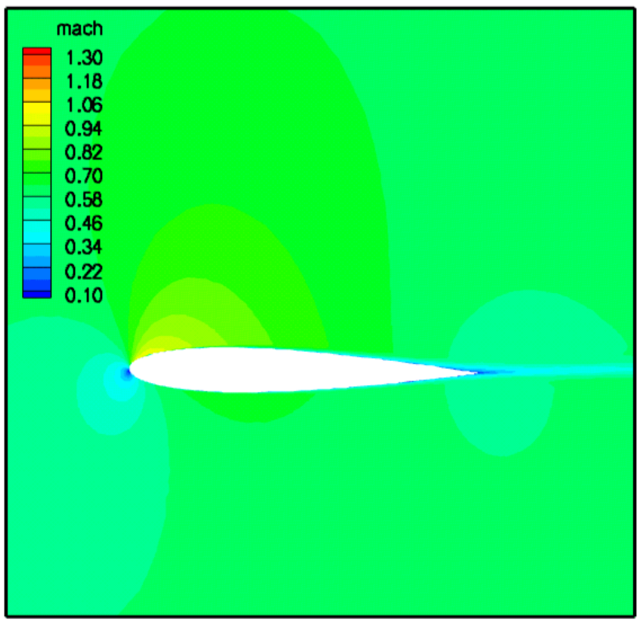


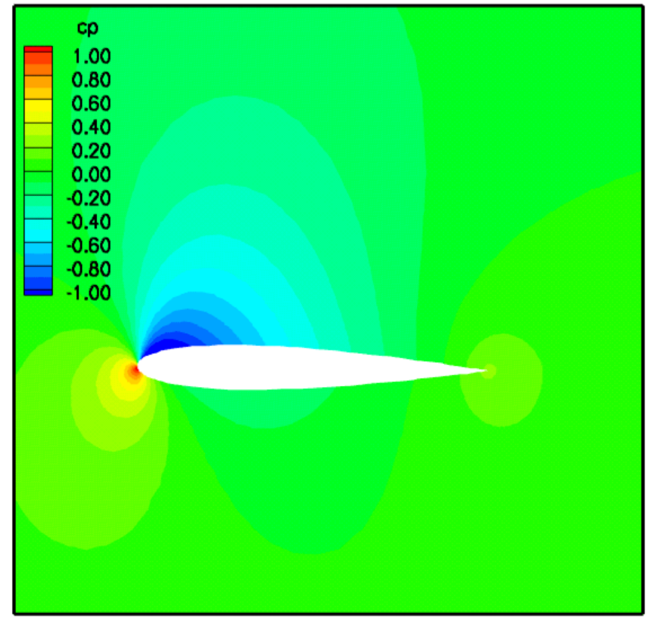
Subiteration Lift & PM, Final 10 Steps
(subit_force_history.lay)



Tutorial Case: Pitching Airfoil (8/9)

Mach Number
(mach_animation.lay)





Pressure Coefficient
(cp_animation.lay)

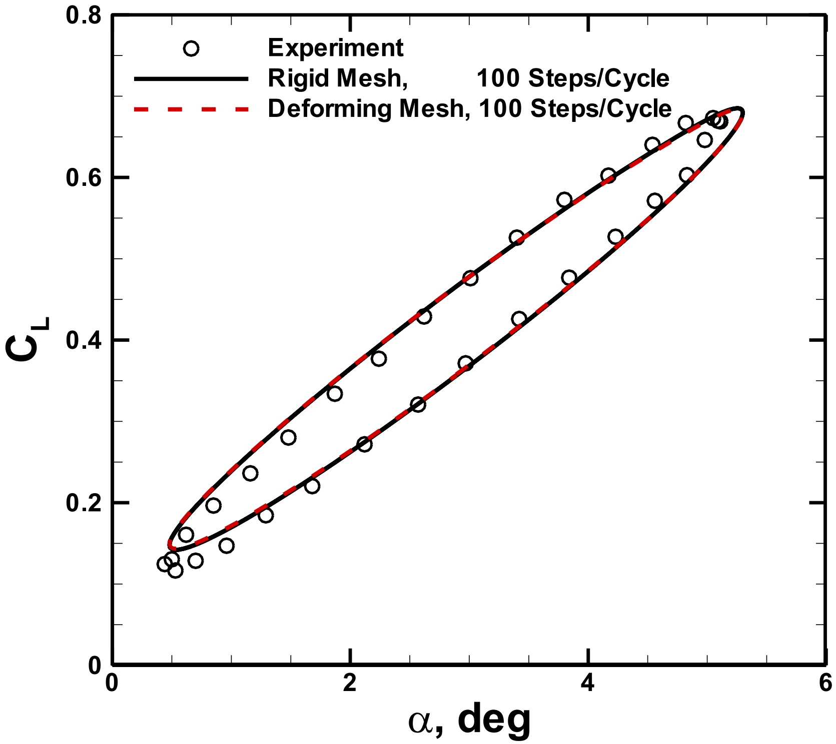
Tutorial Case: Pitching Airfoil (9/9)

Comparison with Landon, AGARD-R-702, Test Data,1982

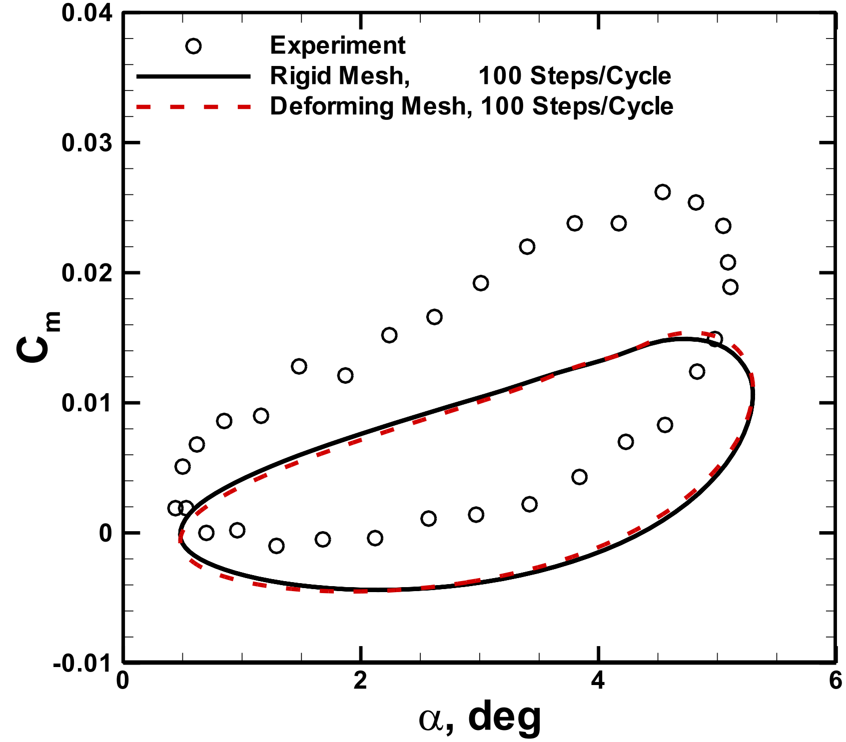
Note: comparison typical of other published CFD results

These plots not generated as part of the tutorial

Lift vs. Alpha



Pitching Moment vs. Alpha



Rigid mesh and deforming mesh produce nearly identical results

Troubleshooting Body / Grid Motion

- When first setting up a dynamic mesh problem, suggest using either the following in the **`&global`** namelist
  - **`body_motion_only = .true.`**
  - **`grid_motion_only = .true.`**
- Both options turn off the flow solution for faster processing (memory footprint is the same however)
  - **`body_motion_only`** especially useful for 1st check of a deforming mesh case since the elasticity solver is also bypassed
  - **`grid_motion_only`** performs all mesh motion, including elasticity solution – in a deforming case this can tell you up front if negative volumes will be encountered
  - Caveat: can't really do this for aeroelastic or 6DOF cases since motion and flow solution are coupled
- Use these with some form of animation output: only *solid boundary* output is appropriate for **`body_motion_only`**; with **`grid_motion_only`** can look at any boundary, or use sampling to look at interior planes, etc.

List of Key Input/Output Files

- Beyond basics like **`fun3d.nml`**, etc.:
  - Set **`moving_grid = .true.`** in **`&global`** namelist
- Input
  - **`moving_body.input`** (else code stops when moving_grid = T)
- Output
  - **`[project]_subhist.dat`**
  - **`PositionBody_N.dat`** (forced motion / 6-DOF only)
  - **`VelocityBody_N.dat`** (forced motion / 6-DOF only)
  - **`AeroForceMomentBody_N.dat`** (forced motion / 6-DOF only)