FUN3D v12.4 Training

Session 10:
Time-Dependent Simulations

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FUN3D

Fully Unstructured Navier–Stokes

Session Scope

- What this will cover

  - How to set up and run time-accurate simulations on static meshes

    - Subiteration convergence: what to strive for and why

    - Nondimensionalization

    - Choosing the time step

    - Input / Output

- What will not be covered

  - Moving-mesh, aeroelastics (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 unsteady flows and may also involve moving geometries
  - Governing equations written in Arbitrary Lagrangian-Eulerian (ALE) form to account for grid speed
  - Nondimensionalization often more involved/confusing/critical
- Compatibility
  - Compressible/incompressible paths
  - Mixed elements; 2D/3D
  - Dynamic grids
  - Not compatible with generic gas model
- Status
  - Incompressible path exercised very infrequently for unsteady flows
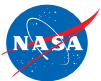
Governing Equations

- Arbitrary Lagrangian-Eulerian (ALE) Formulation

$$\frac{\partial(\vec{Q}V)}{\partial t} = -\oint_{\partial V}\left(\overline{\overline{F}} - \vec{q}\vec{W}^T\right)\cdot\vec{n}dS - \oint_{\partial V}\overline{\overline{F}}_v\cdot\vec{n}dS = \vec{R} \qquad \vec{Q} = \frac{\oint_V \vec{q}\,dV}{V}$$
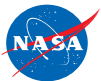
$\vec{W} = $ Arbitrary control surface velocity; Lagrangian if $\vec{W} = (u,v,w)^T$ (moves with fluid); Eulerian if $\vec{W} = 0$ (fixed in space)

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

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

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

- Physical time-level t^n ; Pseudo-time level τ^m

- Want to drive **subiteration residual** $\overline{\vec{R}^{n+1,m}} \rightarrow 0$ using pseudo-time subiterations at each time step – much more later – otherwise you have more error than the expected $O(\Delta t^N)$ truncation error

KEY POINT

http://fun3d.larc.nasa.gov

FUN3D Training Workshop
March 24-25, 2014

NASA

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4

Time Advancement - Namelist Input

- The `&nonlinear_solver_parameters` namelist in the `fun3d.nml` file governs how the solution is advanced in time

- Relevant entries - *default values shown* - some definitely need changing:

```
&nonlinear_solver_parameters
    time_accuracy           = 'steady'  (i.e. not time accurate)
    time_step_nondim        = 0.0
    subiterations           = 0
    schedule_iteration      = 1      50
    schedule_cfl            = 200.0 200.0
    schedule_cflturb        = 50.0   50.0
    pseudo_time_stepping    = "on"
    temporal_err_control    = .false.
    temporal_err_floor      =  0.1
/
```

- Let's look at these in some detail (defer `time_step_nondim` to last)

Time Advancement - Order of Accuracy

- Currently have several types of backward difference formulae (BDF) that are controlled by the `time_accuracy` component:

  - In order of formal accuracy: BDF1 (`1storder`), BDF2 (`2ndorder`), BDF2$_{OPT}$ (`2ndorderOPT`), BDF3 (`3rdorder`), MEBDF4 (`4thorderMEBDF4`)

  - Can pretty much ignore all but BDF2$_{OPT}$ and BDF2

    - BDF1 is least accurate; little gain in CPU time / step over 2nd order; for moving grids can be helpful to start out with BDF1 (rare)

    - BDF3 not guaranteed to be stable; feeling lucky?

    - MEBDF4 only efficient if working to very high levels of accuracy - *including spatial accuracy* - generally ***not*** for practical problems

    - BDF2$_{OPT}$ *(recommended)* is a stable blend of BDF2 and BDF3 schemes; formally 2nd order accurate but error is ~1/2 that of BDF2; also allows for a more accurate estimate of the temporal error for the error controller (p.8)

Time Advancement - Subiterations (1/4)

- Can think of each time step as a mini steady-state problem

- Subiterations (`subiterations` > 0) are essential

  - Subiteration control in *each time step* operates exactly like iteration control in a steady state case:

    - CFL ramping is available for mean flow and turbulence model – however, be aware that ramping schedule should be < `subiterations` or the specified final CFL won't be obtained

      - *We almost never ramp CFL for time-accurate cases*

      - If used, CFL ramping starts over each time step

    - Caution: the *spatial* accuracy flag, `first_order_iterations`, starts over each time step, so make sure you don't have this on

- Pseudo-time term helpful for large time steps

  - We *always* use it in our applications

 - `pseudo_time_stepping = "on"` (default)
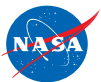
Time Advancement - Subiterations (2/4)

- How many subiterations?
  - In theory, should drive subiteration residual "to zero" each time step – but you cannot afford to do that
  - Otherwise have additional errors other than $O(\Delta t^2)$ (if 2nd order time)

- In a perfect world, the answer is to use the **temporal error controller**
  - `temporal_err_control = .true.`

  - `temporal_err_floor = 0.1` => iterate until the subiteration residual is 1 order lower than the (estimated) temporal error (0.01 => 2)

  - Subiterations kick out when this level of convergence is reached OR subiteration counter > `subiterations`

  - (empirically) 1 order is about the minimum; 2 orders is better, BUT…

  - Often, either the turbulence residual converges slowly or the mean flow does, and the max subiterations you specify will be reached

  - When it kicks in, the temporal error controller is the best approach, and the most efficient; even if it doesn't kick in, it can be informative

Time Advancement - Subiterations (3/4)

- Be wary reaching conclusions about the effect of time-step refinement unless the subiterations are "sufficiently" converged for each size step

- How to monitor and assess the subiteration convergence:

  – Printed to the screen, so you can "eyeball" it

  – With temporal error controller, if the requested tolerance is not met, message(s) will be output to the screen:

    - **`WARNING: mean flow subiterations failed to converge to specified temporal_err_floor level`**

    - **`WARNING: turb flow subiterations failed to converge to specified temporal_err_floor level`**

    - Note: when starting unsteady mode, first timestep *never* achieves target error (no error estimate first step, so target is 0)

    - Note: x-momentum residual (`R_2`) is the mean-flow residual targeted by the error controller

  – Plot it (usually best)

FUN3D
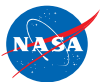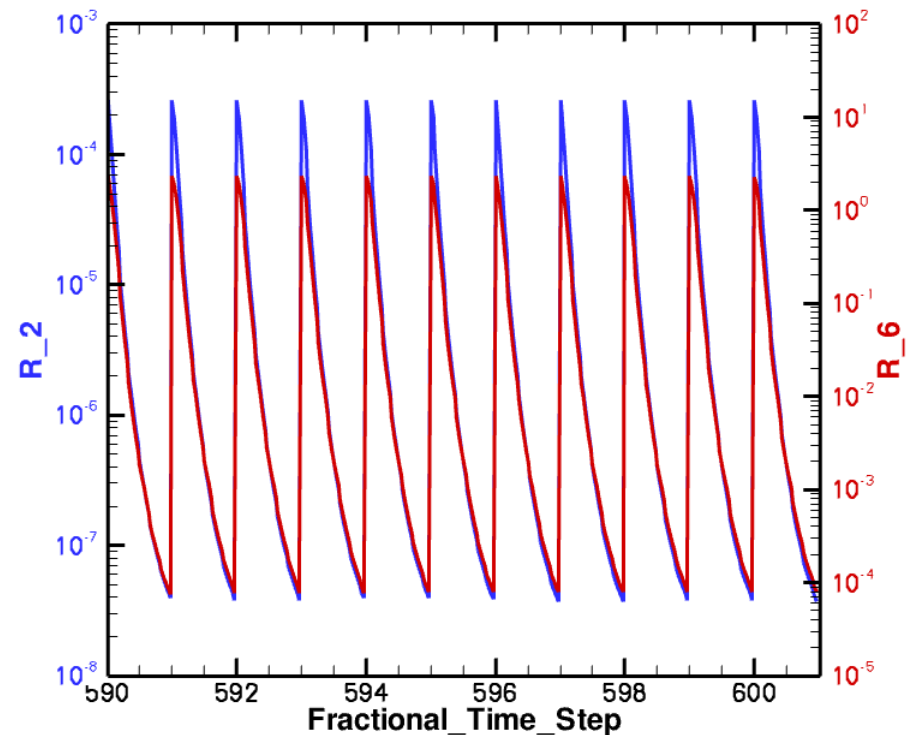Fully Unstructured Navier–Stokes
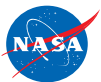
Time Advancement - Subiterations (4/4)

- Tecplot file (ASCII) with subiteration convergence history is output to a file:
`[project]_subhist.dat`
  - Plot (on log scale) `R_2` (etc) vs `Fractional_Time_Step`
 - Also contains Cl, Cd, Cm to assess force convergence in a time step
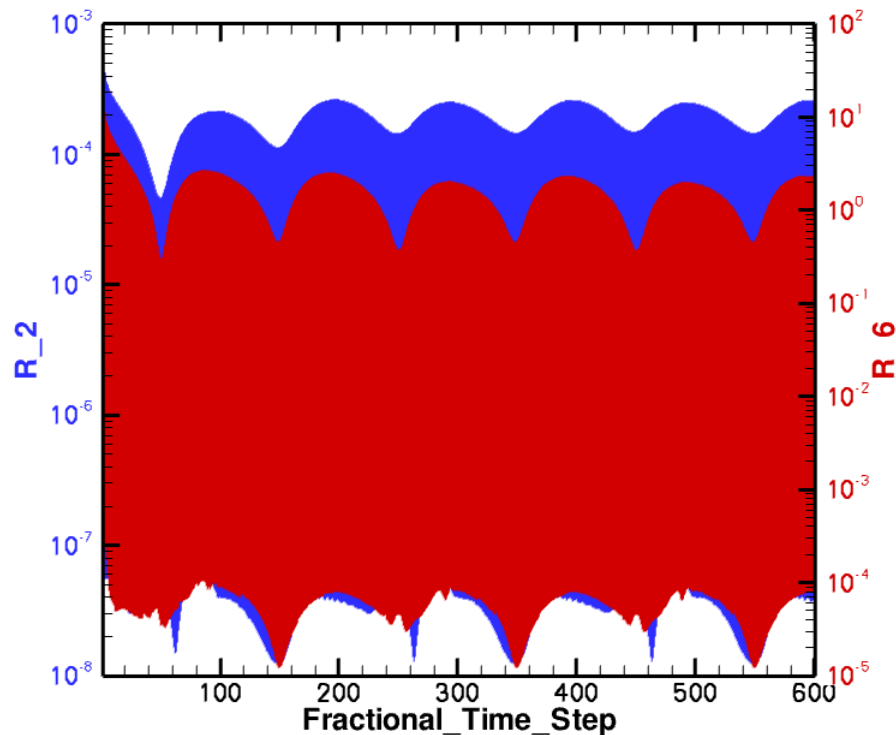
Nondimensionalization of Time

- Notation: * indicates a dimensional variable, otherwise nondimensional; the reference flow state is usually free stream (" ∞ "), but need not be

- Define:
  - L^*_{ref} = reference length of the physical problem (e.g. chord in ft)
  - L_{ref} = corresponding length in your grid (considered *nondimensional*)
  - a^*_{ref} = reference speed of sound (e.g. ft/sec) (compressible)
  - U^*_{ref} = reference velocity (e.g. ft/sec; compressible: U^*_{ref} = Mach a^*_{ref})
  - t^* = time (e.g. sec)

- Then nondimensional time in FUN3D is related to physical time by:
  - $t = t^* a^*_{ref} (L_{ref}/L^*_{ref})$ (compressible)
  - $t = t^* U^*_{ref} (L_{ref}/L^*_{ref})$ (incompressible)
  - *Usually* have $L_{ref}/L^*_{ref} = 1^*$, but need not - e.g. typical 2D airfoil grid
  - L_{ref}/L^*_{ref} appears because Re in FUN3D is input *per unit grid length*

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Determining the Time Step

- Identify a **characteristic time** t^*_{chr} that you need to resolve with some level of accuracy in your simulation; perhaps:

    - Some important shedding frequency f^*_{shed} (Hz) is known or estimated $t^*_{chr} \sim 1 / f^*_{shed}$

    - Periodic motion of the body $t^*_{chr} \sim 1 / f^*_{motion}$

    - A range of frequencies in a DES-type simulation $t^*_{chr} \sim 1 / f^*_{highest}$

    - If none of the above, you can estimate the time it takes for a fluid particle to cross the characteristic length of the body, $t^*_{chr} \sim L^*_{ref} / U^*_{ref}$

    - $t_{chr} = t^*_{chr} a^*_{ref} (L_{ref}/L^*_{ref})$ (comp) $t_{chr} = t^*_{chr} U^*_{ref} (L_{ref}/L^*_{ref})$ (incomp)

- Say you want N time steps within the characteristic time:

    - $\Delta t = t_{chr} / N =$ `time_step_nondim`

- Figure an absolute *minimum* of N = 100 for reasonable resolution of t_{chr} with a 2nd order scheme - really problem dependent (*frequencies > f* may be important*); but don't over resolve time if space is not well resolved too
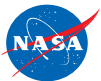
Example - Unsteady Flow at High Alpha (1/7)

- Consider flow past a (2D) NACA 0012 airfoil at 45° angle of attack - the flow separates and is unsteady

  - Re_{c*} = 4.8 million, M_{ref} = 0.6, *assume* a^*_{ref} = 340 m/s

  - chord = 0.1m, chord-in-grid = 1.0 so L_{ref}/L^*_{ref} = 1.0/0.1 = 10 (m^{-1})

  - Say we know from experiment that lift oscillations occur at ~450 Hz

  - t^*_{chr} = 1 / f^*_{chr} = 1 / 450 Hz = 0.002222 s

  - t_{chr} = t^*_{chr} a^*_{ref} (L_{ref}/L^*_{ref}) = (0.002222)(340)(10) = 7.555

  - Δ t = t_{chr} / N so Δ t = 0.07555 for 100 steps / lift cycle

  - By way of comparison, for M = 0.6, a^*_{ref} = 340 m/s, and L^*_{ref} = 0.1 m it takes a fluid particle ~ (0.1)/(204) = 0.00049 s to pass by the airfoil; this leads to smaller, more conservative estimate for the time step, by about a factor of 4
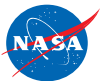
Example - Unsteady Flow (2/7)
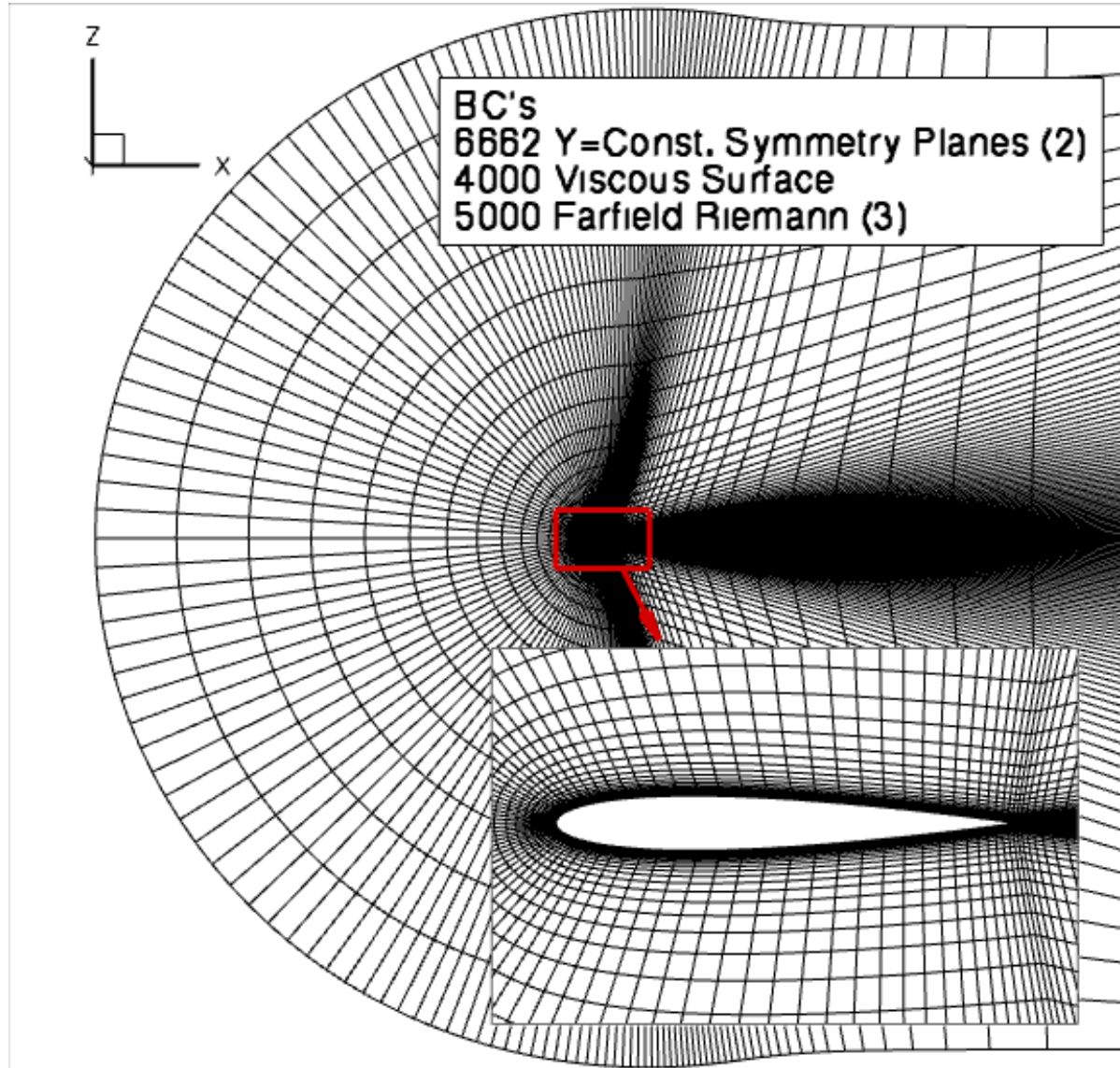
Example - Unsteady Flow (3/7)

- Flow viz: output u-velocity and y-component of vorticity

- Relevant fun3d.nml namelist data

```
&project
    project_rootname = "n0012_i153"
    case_title = "NACA 0012 airfoil, 2D Hex Mesh"
/
&governing_equations
    viscous_terms = "turbulent"
/
&reference_physical_properties
    mach_number      = 0.60
    reynolds_number = 4800000.00
    temperature      = 520.00
    angle_of_attack = 45.0
/
&force_moment_integ_properties
    x_moment_center = 0.25
/
&turbulent_diffusion_models
    turb_model = "sa"
/
```

Example - Unsteady Flow (4/7)

- Relevant fun3d.nml namelist data (cont)

```
&nonlinear_solver_parameters
    time_accuracy        = "2ndorderOPT" ! Our Workhorse Scheme
    time_step_nondim     = 0.07555       ! 100 steps/cycle @ 450 Hz
    temporal_err_control = .true.        ! Enable error-based kickout
    temporal_err_floor   = 0.1           ! Exit 1 order below error estimate
    subiterations        = 30            ! No more than 30
    schedule_cfl         = 50.00 50.00 ! constant cfl each step; no ramping
    schedule_cflturb     = 30.00 30.00
/

&linear_solver_parameters
    meanflow_sweeps   = 50
    turbulence_sweeps = 30
/

&code_run_control
    steps        = 100  ! need ~2000 steps to be periodic from freestream
    restart_read = "on" ! "off": start from freestream
/                       ! "on_nohistorykept": start from steady state soln
&raw_grid
    grid_format = "aflr3"
    data_format = "ASCII"
    twod_mode   = .true.
/
```

Example - Unsteady Flow (5/7)

- Relevant fun3d.nml namelist data (cont)

```
&boundary_output_variables
   primitive_variables = .false. ! turn off default
   y = .false.      ! So tecplot displays correct 2D orientation by default
   u = .true.
   vort_y = .true.
 /                  ! no boundaries specified – default is one of sym. planes
```
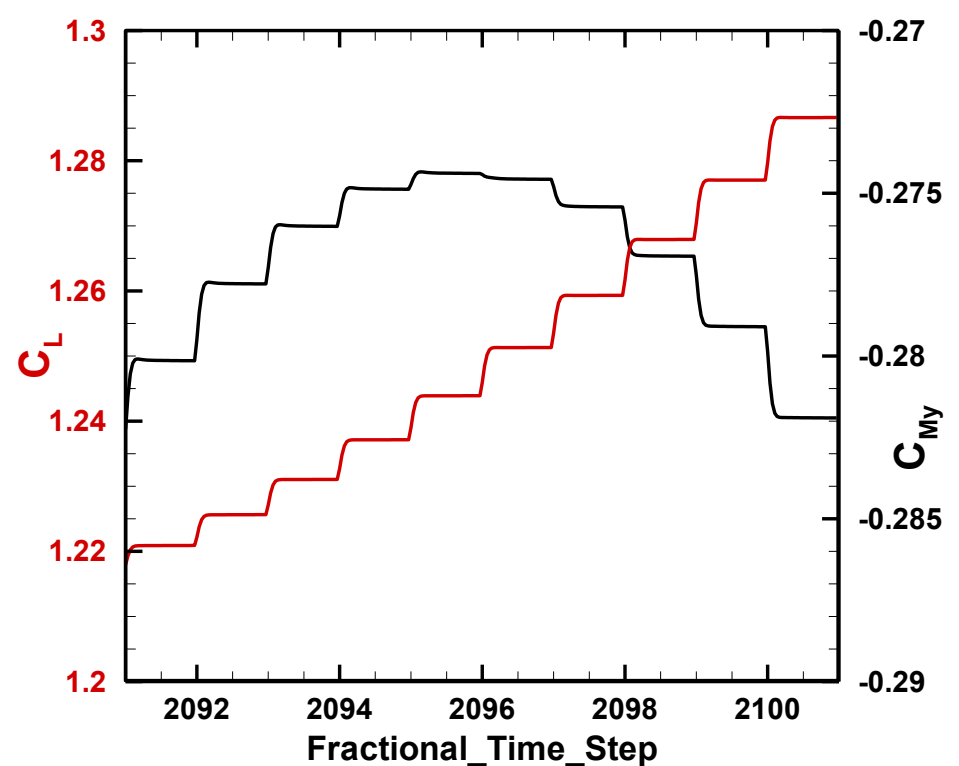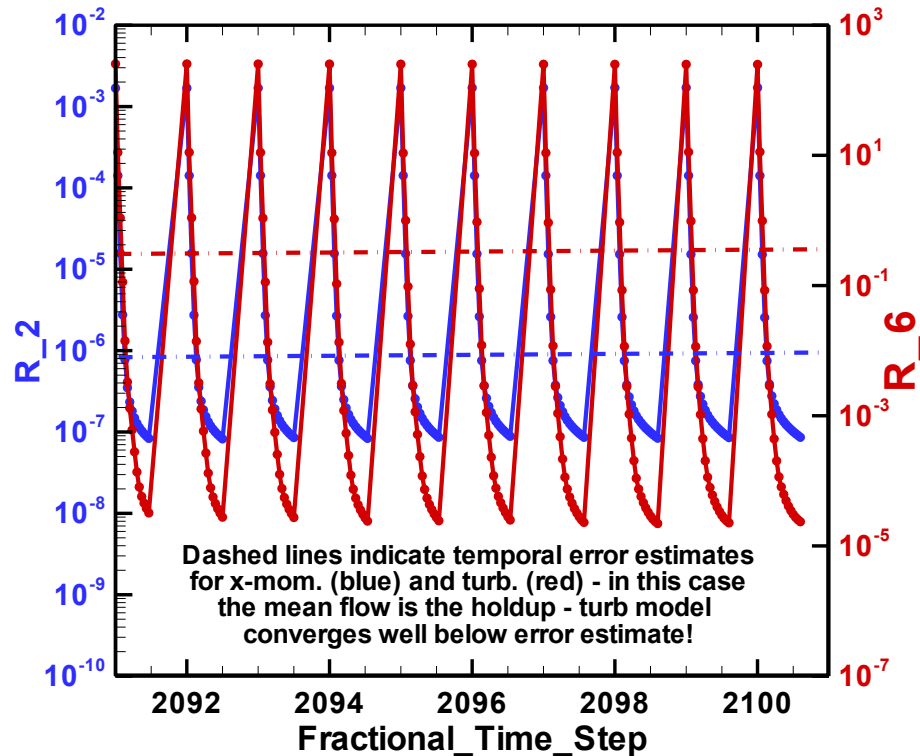
- Subiterations converge? **grep "WARNING" screen_output | wc**

Example - Unsteady Flow (6/7)
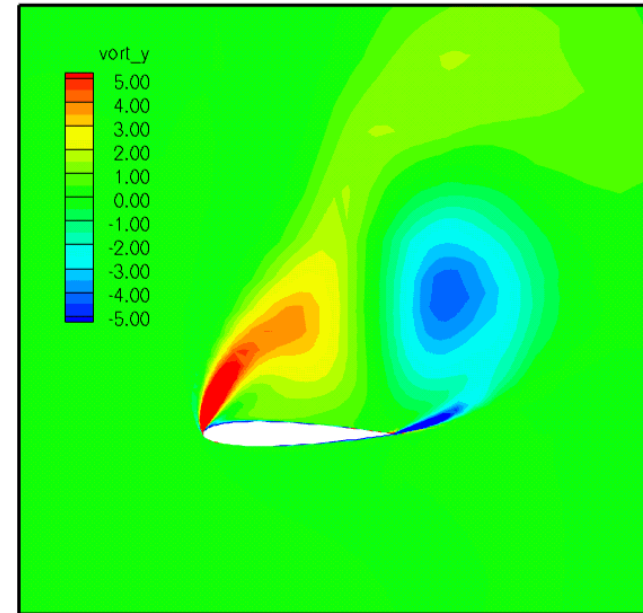
Subiteration Residuals, Final 10 Steps

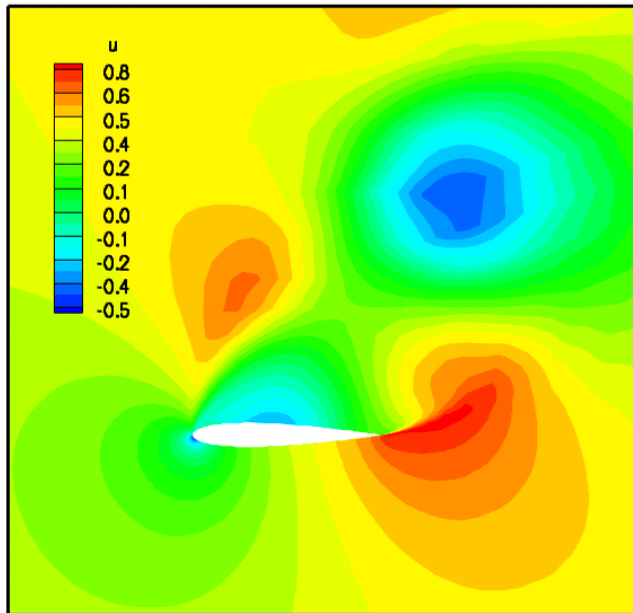Subiteration Lift & PM, Final 10 Steps

Dashed lines indicate temporal error estimates for x-mom. (blue) and turb. (red) - in this case the mean flow is the holdup - turb model converges well below error estimate!

Example - Unsteady Flow (7/7)

- Animation of Results

X-Component of Velocity

Y-Component of Vorticity

List of Key Input/Output Files

- Beyond basics like `fun3d.nml`, etc.:

- Input

  - none

- Output

  - `[project]_subhist.dat`