FUN3D v13.4 Training

Session 17: Rotorcraft Simulations

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Session Scope

- What this will cover
  - Overview of actuator-disk models for rotorcraft
  - Overview of setup for “first principles” articulated-blade rotorcraft simulations using overset grids
    - Rigid Blades
    - Elastic Blades / Loose Coupling to Rotorcraft Comprehensive Codes
- What will not be covered
  - Rotorcraft Comprehensive Code set up and operation
  - All the many critical setup details for the “first principles” approach
- What should you already know
  - Basic time-accurate and dynamic-mesh solver operation and control
  - Rudimentary rotorcraft aeromechanics (collective, cyclic…)

Introduction

- Background
  - FUN3D can model a rotor with varying levels of fidelity/complexity
    - Actuator disk – low-fidelity representation of the rotor - when only the overall rotor influence on the configuration is needed
    - Articulated-blade system (cyclic pitch, flap, lead-lag), with or without aeroelastic effects – if detailed rotor airloads are needed
    - Rotating noninertial frame – steady-state problem for rigid, isolated, fixed-pitch blades
  - Aeroelastic effects require coupling with a rotorcraft “comprehensive” analysis (CA) code
    - CA solver can also provide rotor trim
- Compatibility
  - Coupled to CAMRAD II, DYMORE (Open Source) and RCAS CA codes
- Status
  - Less experience / testing with RCAS than with CAMRAD II / DYMORE
  - Interface provided for US Army’s HELIOS rotorcraft framework

Time-Averaged Actuator-Disk Simulations (1/3)

- Actuator disk method utilizes momentum and energy equation source terms to represent the influence of the disk
  - Original implementation by Dave O'Brien (GIT Ph.D. Thesis)
  - HI-ARMS implementation (SMEMRD) by Dave O'Brien ARMDEC adds trim and ability to use C81 airfoil tables (*Not covered*)
- Simplifies grid generation – actuator disk is automatically embedded in computational grid
- Grid refinement in the vicinity of actuator surface improves accuracy - cell sizes of "background" grid should be similar to cell sizes of actuator disk
- Any number of actuator disks can be modeled
- Requires the **`--rotor`** command line option for standard actuator disk
- For SMEMRD, use **`hiarms_flag=.true.`** in **`&hiarms_actuator_disk`** namelist (**`fun3d.nml`**) - user must request SMEMRD; not in FUN3D distribution

Time-Averaged Actuator-Disk Simulations (2/3)

- Different disk loading models available
  - **`RotorType = 1`** actuator disk
    - **`LoadType = 1`** constant Δp (specified thrust coefficient C_T)
    - **`LoadType = 2`** linearly increasing Δp to blade tip (specified C_T)
    - **`LoadType = 3`** blade element based (computed C_T)
    - **`LoadType = 4`** user specified sources, not recommended
    - **`LoadType = 5`** C_T and C_Q radial distributions provided in a file
    - **`LoadType = 6`** Goldstein distribution with optional swirl (specified C_T and C_Q)
  - **`RotorType = 2`** actuator blades (time-accurate) **Not Functional**

Time-Averaged Actuator-Disk Simulations (3/3)

- Actuator disk implementation compatible with the standard steady-state flow solver process (compressible and incompressible)
  - Standard grid formats for the volume grids
  - Standard solver input deck (**`fun3d.nml`**)
  - Standard output is available (**`project.forces`**, **`project_hist.dat`**, **`project_tec_boundary.plt`**)
  - Expect similar solution convergence as a standard steady-state case
    - Screen output includes “Rotor Force Summary” info at each iteration
- Standard actuator disk model is activated in the command line by **`--rotor`**
  - Rotor input deck file (**`rotor.input`**) is required in the local directory
  - **`rotor.input`** contains disk geometry and loading specifications
  - The disk geometry and loading are output in plot3d format in files **`source_grid_iteration#.p3d`** and **`source_data_iteration#.p3d`**

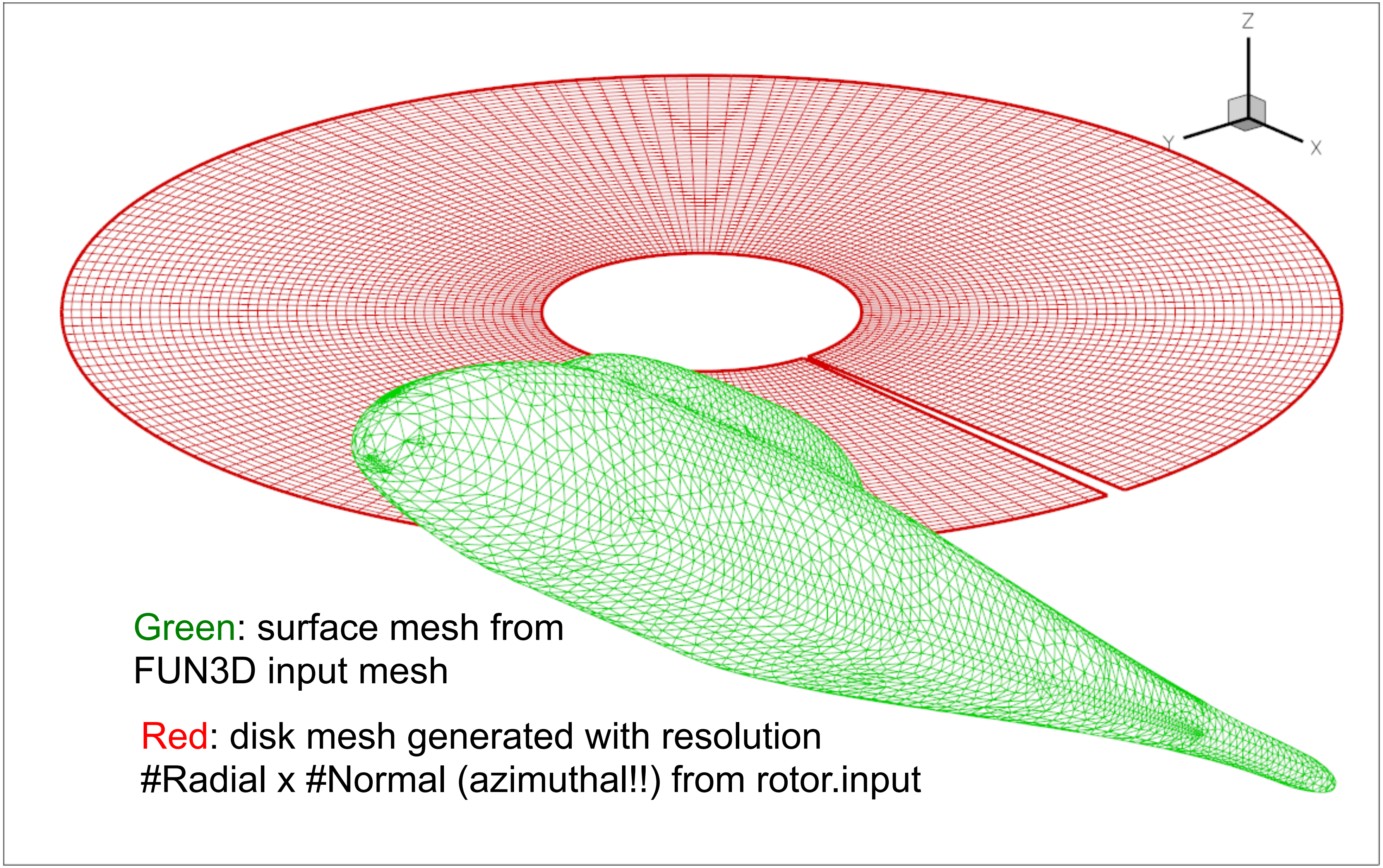
`rotor.input` File

- Constant/linear loading needs only a subset of the data in the file data (manual defines variables)

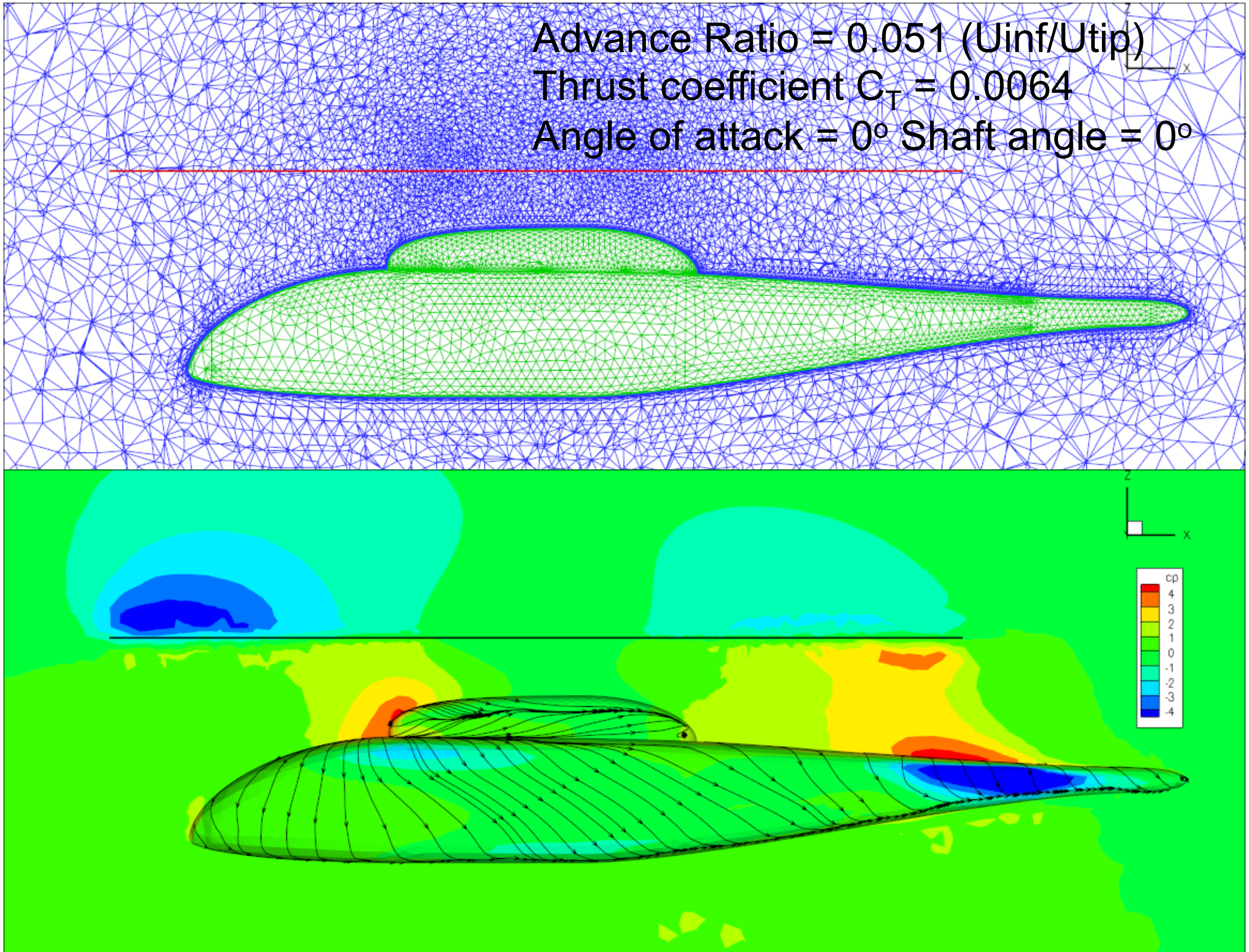
```
  # Rotors   Uinf/Uref  Write Soln   Force Ref  Moment Ref    ! Below we set Uref = Uinf
         1       1.000        1500    0.001117    0.001297    ! Adv Ratio = Uinf/Utip
=== Main Rotor =========================================       ! So here Utip/Uref = 1/AR
Rotor Type   Load Type    # Radial    # Normal  Tip Weight
         1           2          50         180         0.0
  X0_rotor    Y0_rotor    Z0_rotor        phi1        phi2        phi3
     0.696         0.0       0.322        0.00        -0.0        0.00
 Utip/Uref  ThrustCoff  TorqueCoff        psi0  PitchHing/R     DirRot
     19.61      0.0064        0.00         0.0         0.0           0
  # Blades   TipRadius  RootRadius  BladeChord  FlapHinge/R  LagHinge/R
         4       0.861       0.207       0.066       0.051       0.051
 LiftSlope  alpha, L=0         cd0         cd1         cd2
       0.0        0.00       0.002        0.00        0.00
    CL_max      CL_min      CD_max      CD_min       Swirl
      0.00        0.00        0.00        0.00           0
    Theta0  ThetaTwist    Theta1s     Theta1c   Pitch-Flap
       0.0        0.00         0.0         0.0        0.00
 # FlapHar       Beta0      Beta1s      Beta1c
         0         0.0         0.0         0.0
    Beta2s      Beta2c      Beta3s      Beta3c
       0.0         0.0         0.0         0.0
  # LagHar      Delta0     Delta1s     Delta1c
         0         0.0         0.0         0.0
   Delta2s     Delta2c     Delta3s     Delta3c
      0.0          0.0         0.0         0.0
```

Key:
Required for constant/linear actuator disk
Addt'l data for blade element or "first principles" simulations
(all items must have a value, even if unused)

Robin Fuselage with Actuator Disk



Incompressible Robin/Actuator Disk

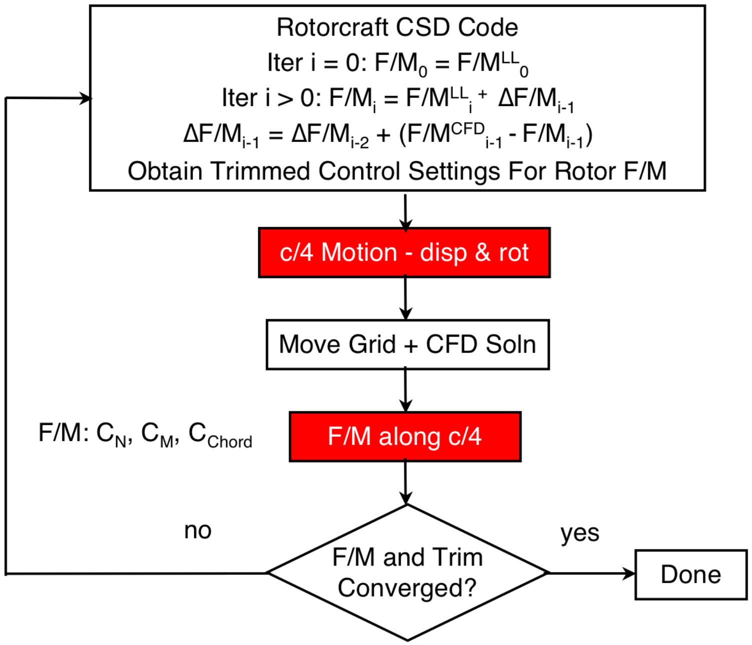


Articulated-Blade Simulations

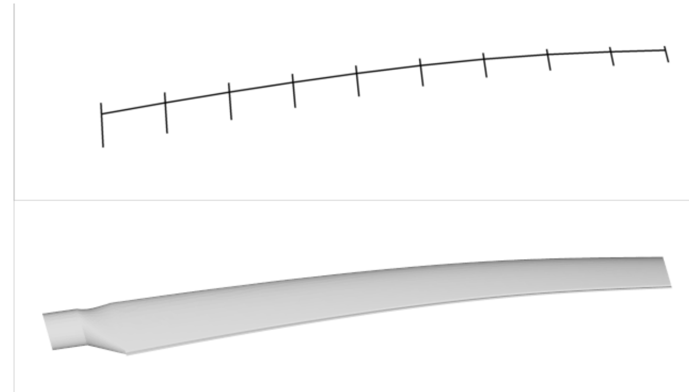
- "First Principles" – rotor flow is computed, not modeled
  - Requires moving, overset grids; blades may be rigid or elastic
- Elastic-blade cases must be coupled to a rotorcraft CA (aka Computational Structural Dynamics, CSD) code such as CAMRAD, DYMORE or RCAS
  - The CA code provides trim solution in addition to blade deformations
  - The "interface" to CAMRAD is through standard OVERFLOW **`rotor_N.onerev.txt`** and **`motion.txt`** type files - translator codes are maintained and distributed by Dr. Doug Boyd, NASA Langley (contact d.d.boyd@nasa.gov)
  - The interface to DYMORE is similar, through **`DeltaAirloads.dat`**, **`DymoreTotalAirloads.dat`** and **`Deflections.dat`** type files - interface codes are maintained by Prof. Olivier Bauchau, U. Maryland
  - RCAS coupling does not require any translator codes (RCAS API)
  - FUN3D has postprocessing utility codes (utils/Rotorcraft/)
  - Many small details - we will not have time to cover

CFD/CA – Loose (Periodic) Coupling

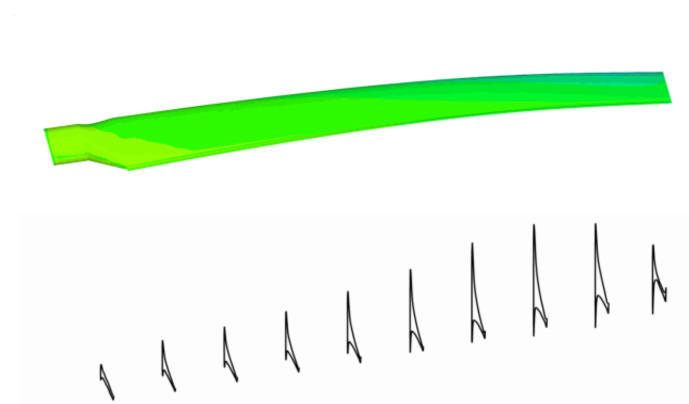
Coupling Process



CA -> CFD



CFD -> CA

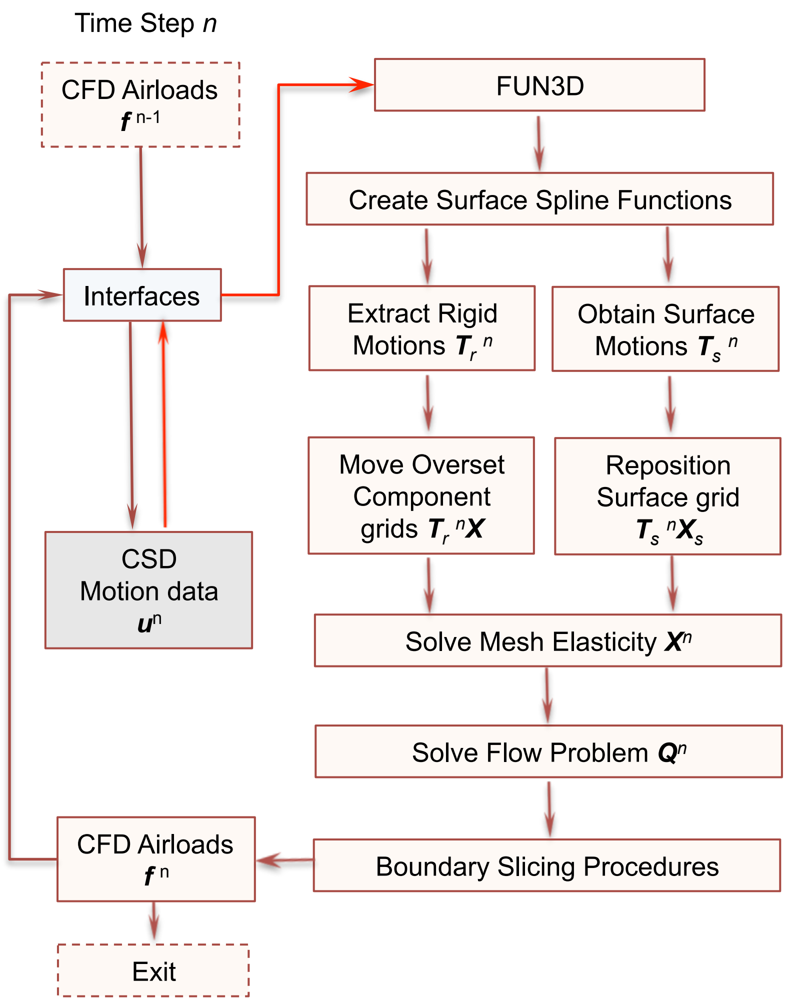


motion.txt file (blade elastic motion) and rotor_onerev.txt file (aero loads) common to FUN3D and OVERFLOW for coupling with CAMRAD

CFD/CAMRAD loose coupling implemented via shell script with error checking

CFD/CA – Tight Coupling

- FUN3D can also couple with CA codes in a tightly coupled manner
  - Similar to a loosely coupled procedure, but...
  - Frequent airloads-displacements data exchange between CFD and CA codes, .e.g., once per time step
  - CFD airloads applied to CA directly
  - Separated solution processes
- Support coupling with DYMORE and RCAS (less experience)
  - All data transferred in memory through interfaces - no file I/O



CFD/CSD tight-coupling algorithm

Rotor-Specific Nondimensional Input (1/2)

- Typically define the flow reference state for rotors based on the tip speed; thus in **`rotor.input`**, set $\mathtt{U_{tip}/U_{ref}}$ **`= 1.0`** (data line 4)
- This way, $\mathtt{U_{inf}/U_{ref}}$ (data line 1) is equivalent to $\mathtt{U_{inf}/U_{tip}}$, which is the Advance Ratio, and is usually specified or easily obtained
- Since the reference state corresponds to the tip, the **`mach_number`** in the **`fun3d.nml`** file should be the tip Mach number, and the **`reynolds_number`** should be the tip Reynolds number
- Nondimensional rotation rate: not input directly, but it is output to the screen; you might want to explicitly calculate it up front as a later check:

$\Omega^* = U^*_{tip} / R^*$ (rad/s, R^* the rotor radius)

and recall $\Omega = \Omega^* (L^*_{ref} / L_{ref}) / a^*_{ref}$ (compressible)

so with $a^*_{ref} = U^*_{ref} / M_{ref}$ and taking $L^*_{ref} = R^*$ $(L_{ref} = R)$

$\Omega = M_{ref} (U^*_{tip} / U^*_{ref}) / R$ (compressible)

$\Omega = U^*_{tip} / U^*_{ref} / R$ (incompressible)

Rotor-Specific Nondimensional Input (2/2)

- Nondimensional time step:

Note new easy Δt input introduced in slide 19

time for one rev: $T^* = 2\pi / \Omega^* = 2\pi R^* / U^*_{tip}$ (s)

and recall $t = t^* a^*_{ref} (L_{ref} / L^*_{ref})$ (compressible)

so with $L^*_{ref} = R^*$ we have

$T = a^*_{ref} (R / R^*) 2\pi R^* / U^*_{tip} = 2\pi R / (M_{ref} U^*_{tip} / U^*_{ref})$ (nondim time / rev)

For N steps per rotor revolution:

$\Delta t = 2\pi R / (N M_{ref} U^*_{tip} / U^*_{ref})$ (compressible)

$\Delta t = 2\pi R / (N U^*_{tip} / U^*_{ref})$ (incompressible)

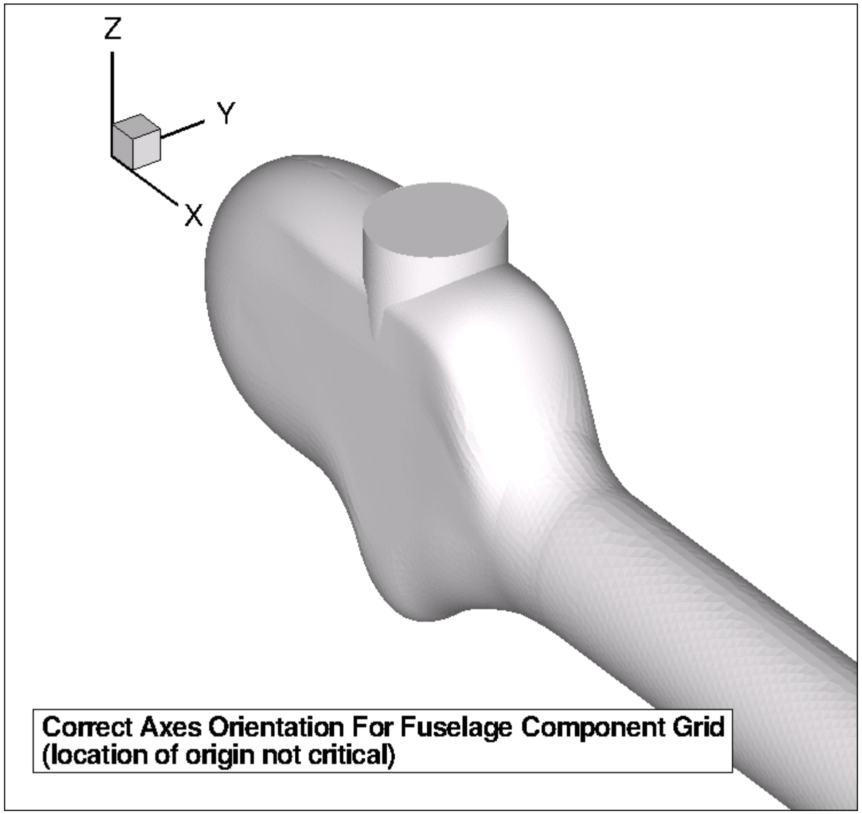
- Note: the azimuthal change per time step is output to the screen in the `Rotor info` section. Make sure this is consistent, to a high degree of precision (say at least 4 digits), with your choice of N steps per rev – you want the blade to end up very close to 360 deg. after multiple revs!
- Formulas above are general, but recall we usually have ref = tip, at least for compressible flow

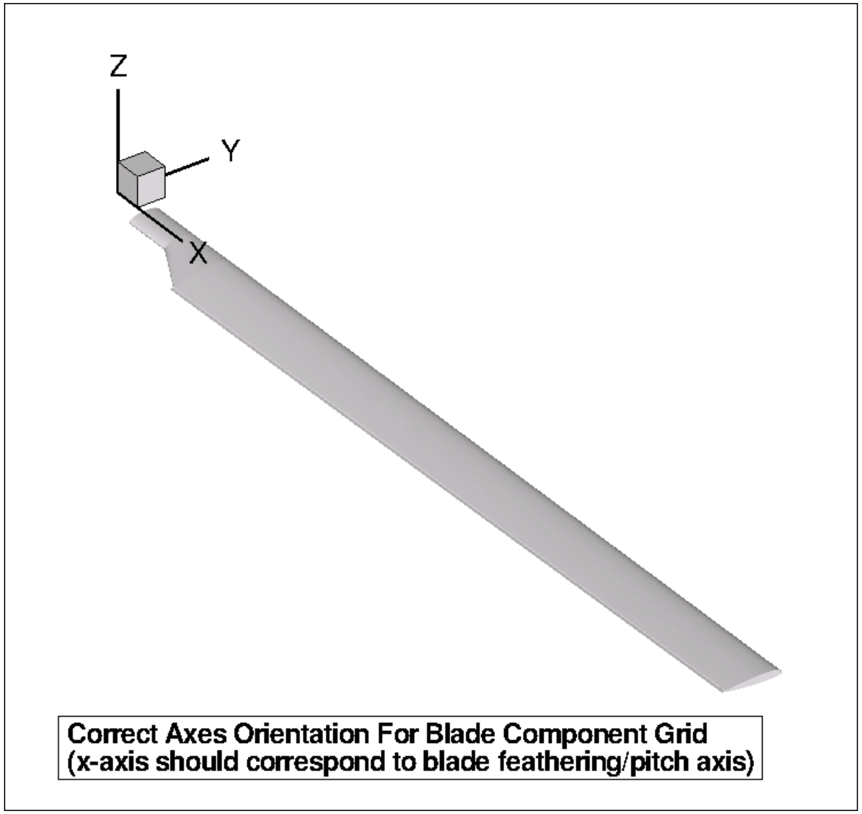
`dci_gen` Preprocessor (1/3)

- A rudimentary code to simplify rotorcraft setup (/utils/Rotocraft/dci_gen)
  - Uses libSUGGAR++ routines
  - Takes a single blade grid and a single fuselage / background grid (extending to far field) and assembles them into an N-bladed rotorcraft
  - Requires **`rotor.input`** file (number of blades defined there)
  - Creates the SUGGAR++ XML file (**`Input.xml_0`**) needed by FUN3D
  - Generates, using libSUGGAR++ calls, the initial (t = 0) dci file and composite grid needed by FUN3D
  - Generates the composite-grid "mapbc" files needed by FUN3D
  - Component grids *must* be oriented as shown on following slide
    - Blade must have any "as-built" twist incorporated
    - If grids do not initially meet the orientation criteria, can use SUGGAR++ to rotate them *before* using **`dci_gen`**

`dci_gen` Preprocessor (2/3)

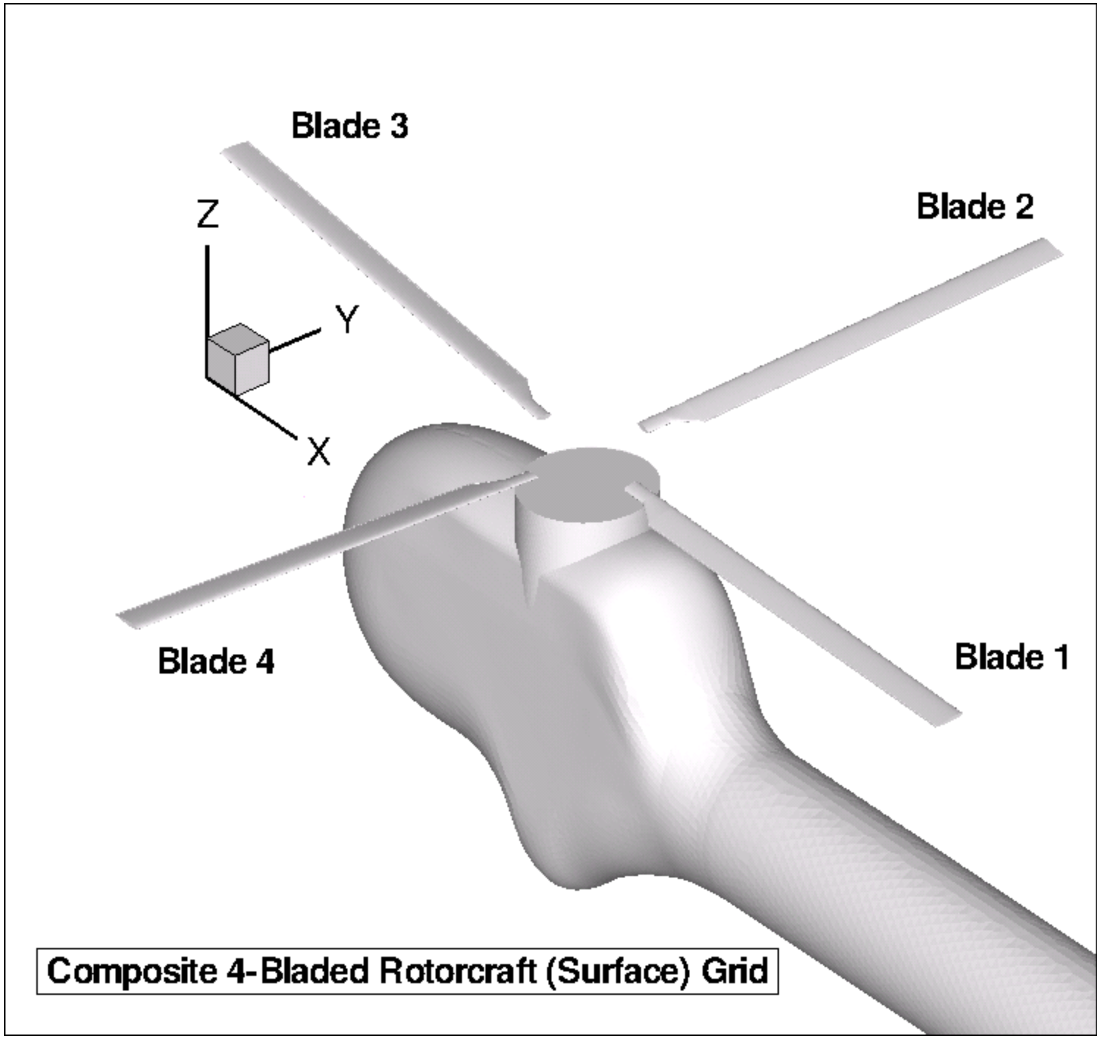
HART II *Component* Grids





`dci_gen` Preprocessor (3/3)

HART II *Composite* Grid



`rotor.input` File

- Articulated rotors need only a subset of the data (manual defines variables)

```
 # Rotors    Uinf/Uref  Write Soln   Force Ref Momment Ref    ! Below we set Uref = Utip
        1        0.245        1500         1.0         1.0    ! Adv Ratio = Uinf/Utip
=== Main Rotor =============================================  ! So here Uinf/Uref = AR
Rotor Type   Load Type    # Radial    # Normal  Tip Weight
         1           1          50         180         0.0
  X0_rotor    Y0_rotor    Z0_rotor        phi1        phi2        phi3
       0.0         0.0         0.0        0.00         0.0        0.00
 Utip/Uref  ThrustCoff  TorqueCoff        psi0  PitchHinge      DirRot
       1.0      0.0064        0.00         0.0      0.0466           0
  # Blades   TipRadius  RootRadius  BladeChord   FlapHinge    LagHinge
         4     26.8330      2.6666       1.741      0.0466      0.0466
 LiftSlope  alpha, L=0         cd0         cd1         cd2
      6.28        0.00       0.002        0.00        0.00
    CL_max      CL_min      CD_max      CD_min       Swirl
      1.50       -1.50        1.50       -1.50           0
    Theta0  ThetaTwist     Theta1s     Theta1c  Pitch-Flap
       0.0        0.00         0.0         0.0        0.00
 # FlapHar       Beta0      Beta1s      Beta1c
         0         0.0         0.0         0.0
    Beta2s      Beta2c      Beta3s      Beta3c
       0.0         0.0         0.0         0.0
  # LagHar      Delta0     Delta1s     Delta1c
         0         0.0         0.0         0.0
   Delta2s     Delta2c     Delta3s     Delta3c
     0.0           0.0         0.0         0.0
```

Key:
Required for rigid and elastic
Additional for untrimmed rigid
Unused (must have a value)

Input For Articulated-Blade Simulations (1/2)

- Except as noted, inputs pertain to both untrimmed/rigid-blades and trimmed/elastic blades
- Run as time-dependent, so will need to set time step as per slide 14
- Required additional **`fun3d.nml`** input

```
&global
   moving_grid = .true.
   slice_freq  = 1                  (optional if rigid untrimmed)
/
&rotor_data
   overset_rotor = .true.
/
&overset_data
   overset_flag       = .true.
   dci_on_the_fly     = .true.   (potentially optional if rigid)
   dci_period         =  360     (assuming 1 deg. per time step)
   reuse_existing_dci = .true.
/
&nonlinear_solver_parameters
   time_step_dpsi     = 1.0      (azimuthal deg. per time step)
/
```

Input For Articulated-Blade Simulations (2/2)

- The **`moving_body.input`** file is somewhat simplified since much of the motion description is handled by **`rotor.input`** – all we need do is to define the moving bodies and provide the SUGGAR++ XML file if required

```
 &body_definitions
   n_moving_bodies      = 4                 (e.g., for 4-bladed rotor)
   body_name(1)         = 'rotor1_blade1'  (same as in xml file)
   n_defining_bndry(1) = 2
   defining_bndry(1,1) = 3
   defining_bndry(1,2) = 4
   mesh_movement(1)     = 'rigid+deform'  (or just 'rigid' for
                                            for rigid blade case)
   …    (etc. for blades 2-4)
/
&composite_overset_mesh
   input_xml_file = "Input.xml_0"   (potentially optional if rigid
/                                    and have precomputed dci)
```

- Note: **`motion_driver`** *not* set in **`&body_definitions`** (in contrast to any other moving-grid case); also *no* **`&forced_motion`** input

CAMRAD Considerations

- User must set up basic CAMRAD II scripts; the **`RUN_LOOSE_COUPLING`** script provided with FUN3D requires 3 distinct, but related CAMRAD scripts
  - **`basename_ref.scr`**
    - Used to generate the reference motion data used by CAMRAD
    - Set this file to use rigid blades; zero collective/cyclic; no trim
  - **`basename_0.scr`**
    - Used for coupling/trim cycle "0"
    - Set up for elastic blades with trim; use CAMRAD aerodynamics exclusively (no delta airloads input); simplest aero model will suffice
  - **`basename_n.scr`**
    - Used for all subsequent coupling/trim cycles
    - Set up for elastic blades with trim; use same simple CAMRAD aerodynamics but now with delta airloads input

DYMORE Considerations

- For coupling with DYMORE, **`fsi_tight_coupling.input`** file is required - both loose and tight coupling procedures

```
./dymore5_baseline/uh60_4bl.dym         ! Main DYMORE input
1.0                                      ! grid unit ratio
1                                        ! ramping parameters for motions
```

- You can put all DYMORE input decks under the FUN3D run directory - but suggest to create a subdirectory to store all DYMORE input decks (and outputs); in the above example, **`./dymore5_baseline`** is the subdirectory
- Note that more info will be added to **`fsi_tight_coupling.input`** file for FUN3D/DYMORE multidisciplinary design optimization (referred to Multidisciplinary Design Session)

Blade Surface "Slicing"

- Boundary surface (rotor blade) slicing is *required* for coupled CFD/CA simulations; also useful for rigid-blade cases - this is what generates the data in **`rotor_1.onerev.txt, rotor_1.onerev_inertial.txt`**

```
$slice_data
 replicate_all_bodies    = .true.          ! do the following the same on all blades
 output_sectional_forces = .false.         ! just lots of data we usually don't need
 tecplot_slice_output    = .false.         ! ditto
 slice_x(1)              = .true.,         ! x=const slice - in original blade coords
 nslices                 = -178,           ! no. slices; "-" means give start and delta
 slice_location(1)       = 2.8175,         ! x-location to slice (starting slice)
 slice_increment         = .13416666666    ! delta slice location each successive slice
 n_bndrys_to_slice(1)    = 1,              ! 1 bndry to search
 bndrys_to_slice(1,1)    = 2,              ! indicies:(slice,bdry) lumping made life easy
 slice_frame(1)          = 'rotor1_blade1', ! ref. frame in which to slice - use body name
 te_def(1)               = 20,             ! look for 2 corners in 20 aft-most segments
 le_def(1)               = 30,      ! search 30 fwd-most pts for one most distant from TE
 chord_dir(1)            = -1,             ! Recall goofy original blade coord system
/
```

- Note: "slicing" useful for applications other than rotorcraft; see website

Untrimmed Rigid-Blade Simulations

- Overview of the basic steps
  1. Prepare rotor blade and fuselage grids, with proper axis orientation
  2. Set up the **`rotor.input`** file based on flight conditions
  3. Run the **`dci_gen`** utility to create a composite mesh and initial dci data
  4. Set up **`fun3d.nml`** and **`moving_body.input`** files
  5. Optionally set up the &**`slice_data`** namelist in the **`fun3d.nml`** file
  6. Run the solver; the number of time steps required is case dependent – usually at least 3 revs for rigid blades

Trimmed, Elastic-Blade Simulations (1/2)

- Overview of the basic steps; steps 1-4 are the same as for the untrimmed rigid-blade case; use of CAMRAD is assumed

5. Set up the **`&slice_data`** namelist; set **`slice_freq = 1`** *not optional*
6. In **`&rotor_data`** namelist, set **`comprehensive_rotor_coupling='camrad'`**
7. Set up the 3 CAMRAD run-script templates as per slide 21
8. Set up the **`RUN_LOOSE_COUPLING`** run script (a c-shell script geared to PBS environments); user-set data is near the top – sections 1 and 2
9. Set up the **`fun3d.nml_initial`** and **`fun3d.nml_restart`** files used by the run script; typically set the time steps in the initial file to cover 2 revs, and $2/N_{blade}$ revs in restart version
10. Before using the run script make sure all items it needs are in place
11. Number of coupling cycles required for trim will vary, but 8-10 is typical for low-moderate thrust levels; high thrust cases near thrust boundary may require 10-15; user judges acceptable convergence

Trimmed, Elastic-Blade Simulations (2/2)

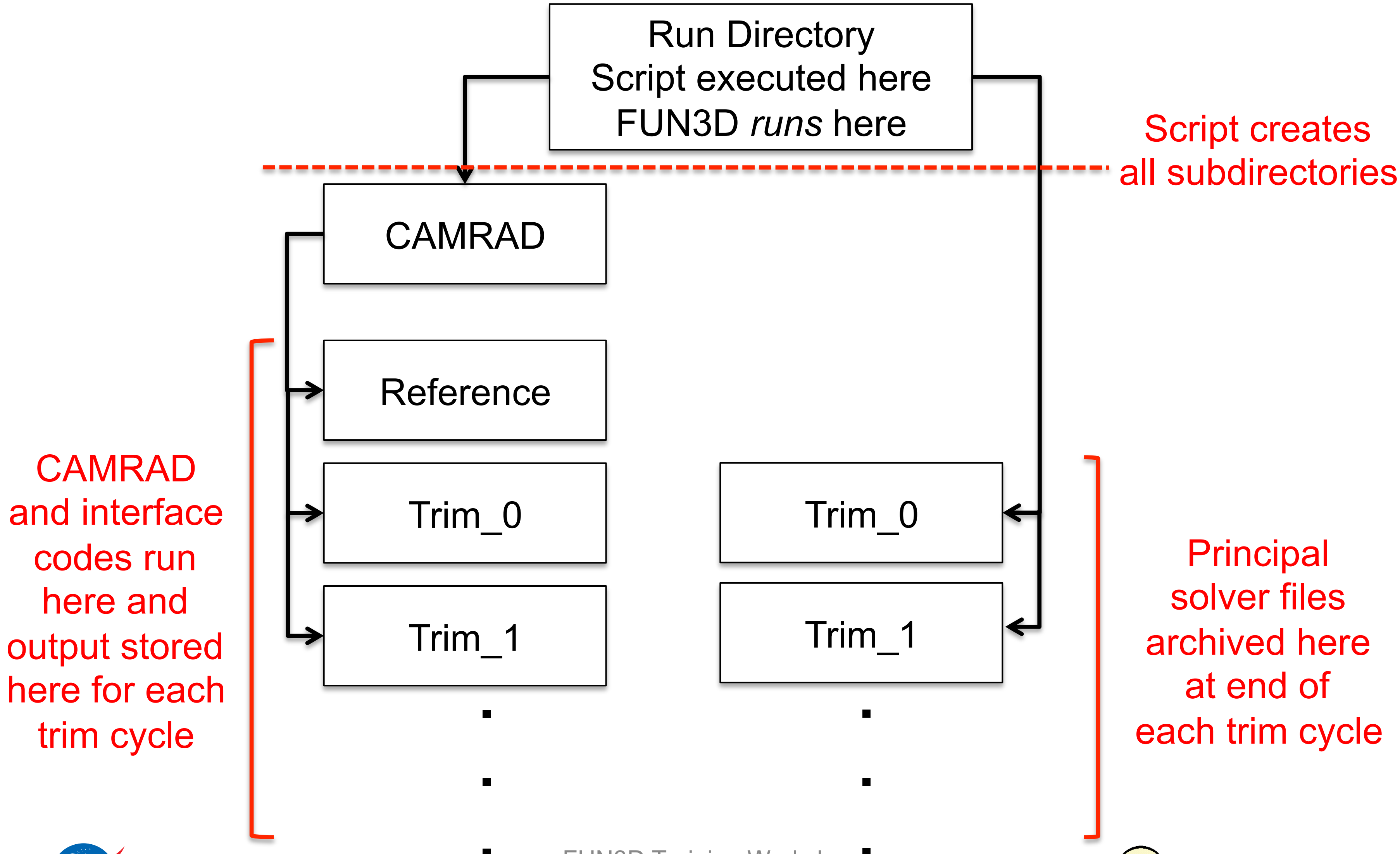
- Overview of the basic steps; steps 1-5 are the same as for CAMRAD case; use of DYMORE is assumed (*loose coupling*)
  6. Set up **`&rotor_data`** namelist; set

     `comprehensive_rotor_coupling = 'dymore'`

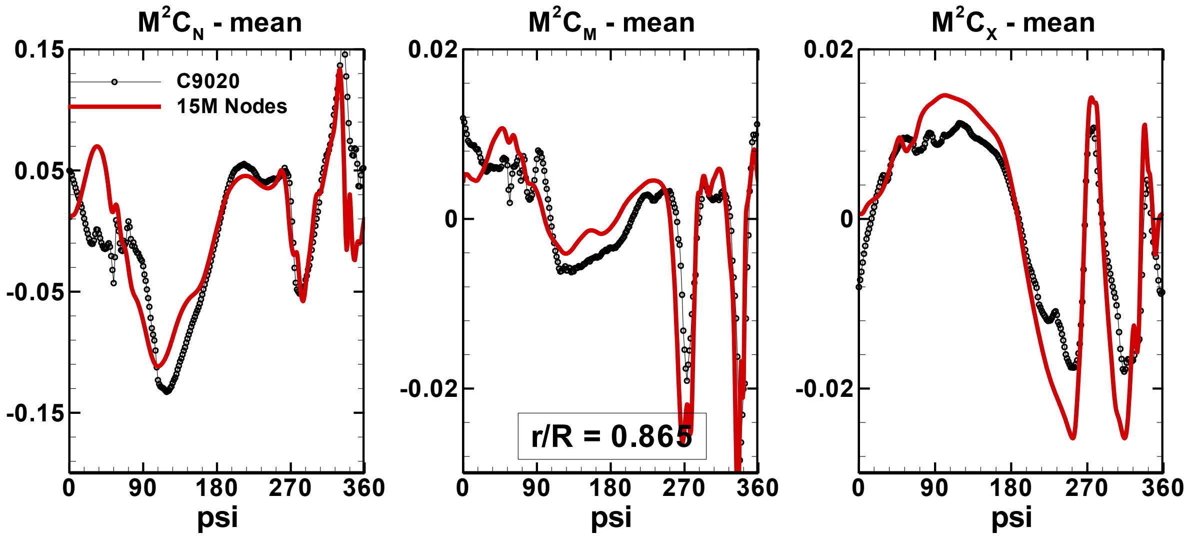
     `niters_cfd(1,1:2) = 360, 180`

     - number of CFD time steps used for 1st and all subsequent loose-coupling iterations before airloads transferred to DYMORE
  7. Set up **`fsi_tight_coupling.input`** file as per slide 22
  8. Run DYMORE static analysis (no wind)
  9. Run DYMORE dynamic analysis (i.e., no delta airloads; using internal low-fidelity aerodynamics) to get initial blade deflections with trim
  10. Run FUN3D - total number of CFD time steps for all coupling iterations is controlled by **`steps`** parameter in **`&code_run_control`** namelist
- FUN3D runs *tight coupling* - in **`&rotor_data`** namelist, set **`comprehensive_rotor_coupling = 'dymore_tight'`**; in **`fsi_tight_coupling.input`** file, set DYMORE input name accordingly

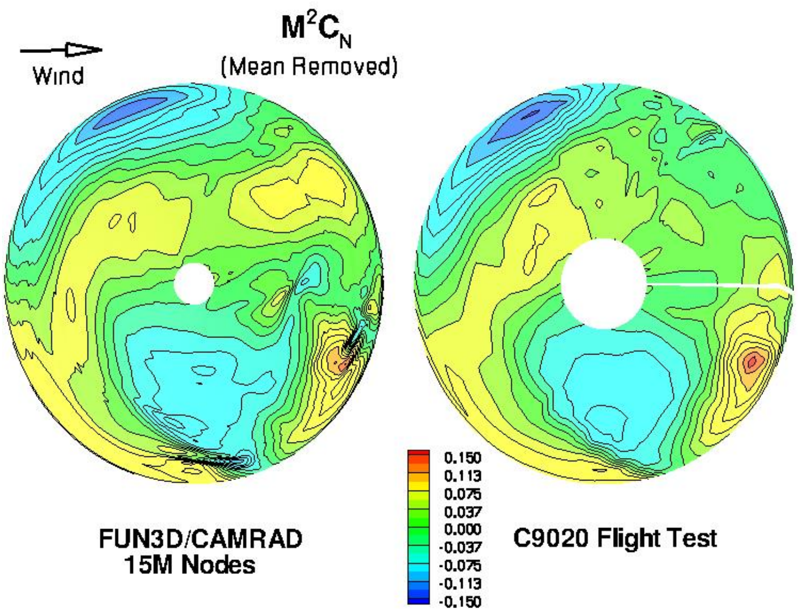
RUN_LOOSE_COUPLING Directory Tree (CAMRAD)

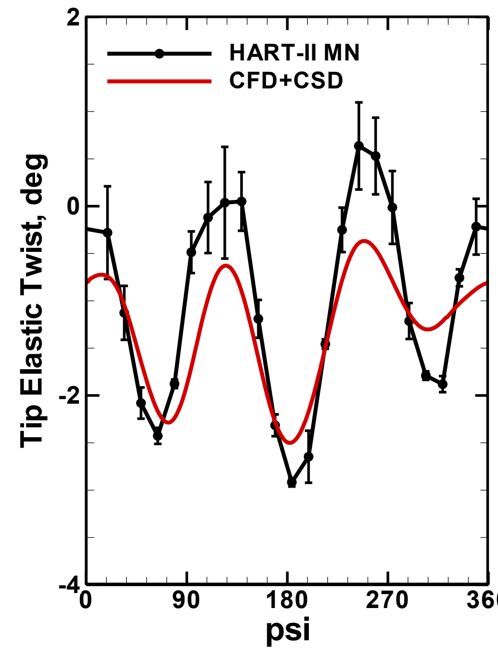


Postprocessing (utils/Rotorcraft/)



Sample Plots Possible Via process_rotor_airloads.f90 Output





Noninertial Reference Frame (1/2)

- For ***isolated, rigid*** an improvement in solution efficiency may be obtained by transforming to a coordinate system that rotates with the rotor
- FUN3D implements a very limited subset of possible noninertial frames:
  - Constant rotation rate
  - Free-stream flow limited to
    - Quiescent (e.g., rotor in hover)
    - Flow aligned with axis of rotor (e.g., ascending/descending rotor; prop in forward flight at 0 AoA)
- In this noninertial rotating frame, the flow is assumed steady
- Can be used in conjunction with overset grids to allow pitch/collective changes to rotor without regridding
- The noninertial capability has other limited applications in addition to rotors – e.g., aircraft in a steady loop

Noninertial Reference Frame (2/2)

- **`fun3d.nml`** input for noninertial frame solutions (example for rotor spinning about z-axis)

```
&noninertial_reference_frame
  noninertial = .true.
  rotation_center_x = 0.0  !rotation axis passes through this pt.
  rotation_center_y = 0.0
  rotation_center_z = 0.0
  rotation_rate_x   = 0.0
  rotation_rate_y   = 0.0
  rotation_rate_z   = 0.2
/
```

- The nondimensional rotation rate is determined as shown on slide 13
- Flow-visualization output (boundary, volume, sampling) will be relative to the noninertial frame