FUN3D v12.7 Training

Session 17: Rotorcraft Simulations

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Session Scope

- What this will cover
  - Overview of actuator-disc 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
    - As an actuator disk – low-fidelity representation of the rotor - when only the overall rotor influence on the configuration is needed
    - As rotating, articulated-blade system (cyclic pitch, flap, lead-lag), with or without aeroelastic effects - if detailed rotor airloads are needed
      - Trim and aeroelastic effects require coupling with a rotorcraft "comprehensive" code
    - As a steady-state problem for rigid, isolated, fixed-pitch blades in a rotating noninertial frame
- Compatibility
  - Coupled to the CAMRAD II and RCAS comprehensive codes
- Status
  - Far less experience / testing with RCAS than with CAMRAD II
  - Near future: hooks to 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 (refinement in the vicinity of actuator surface improves accuracy)
- Any number of actuator disks can be modeled
- Requires the `--rotor` command line option (`--hiarms_rotor` for SMEMRD). See `rotor.input` section in user manual for full details

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

- Different disk loading models available
  - **`RotorType = 1`** actuator disk
    - **`LoadType = 1`** constant (specified thrust coefficient C_T)
    - **`LoadType = 2`** linearly increasing to blade tip (specified C_T)
    - **`LoadType = 3`** blade element based (computed C_T)
    - **`LoadType = 4`** not recommended, user specified sources
    - **`LoadType = 5`** C_T and C_Q radial distributions proved 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.tec`**, **`project_tec_boundary.plt`**)
  - Want similar solution convergence as a standard steady-state case
- 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

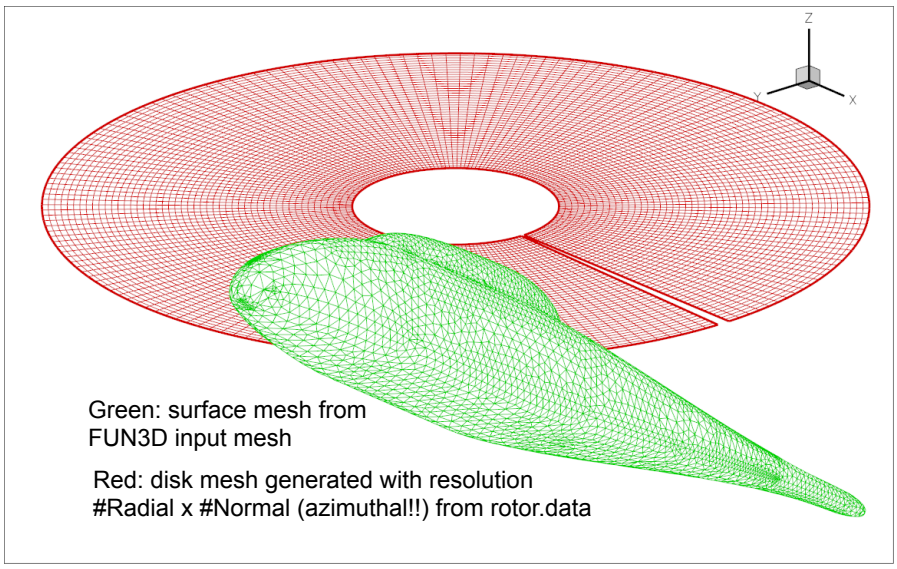
- Constant/linear loading needs only a subset of the data in the file data (manual defines variables)

```
   # 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
```

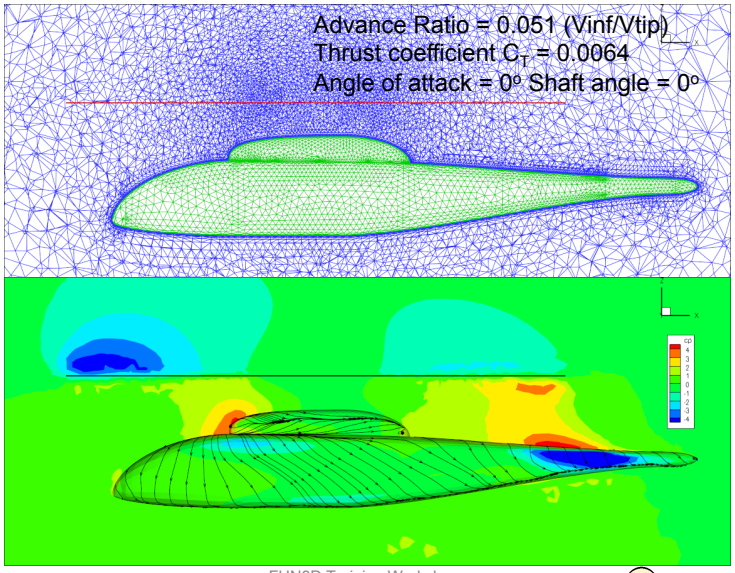
Key:
Required for constant/linear actuator disk
Addt'l data for blade element or "first principles" simulations
(all items must have a value, even if unused)

- Vref=Vtip a bad choice for incompressible – use rotor induced velocity

Robin Fuselage with Actuator Disk



Incompressible Robin/Actuator Disk

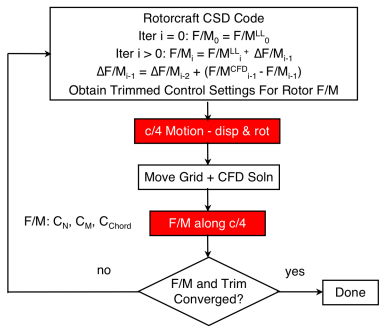


Articulated-Blade Simulations

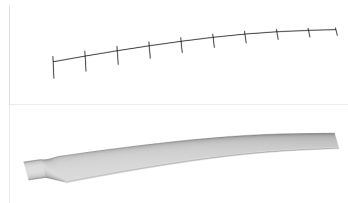
- "First Principles" – rotor flow is computed, not modeled
  - Requires moving, overset grids; blades may be rigid or elastic
- Elastic-blade cases (or *trimmed* rigid-blade cases) must be coupled to a rotorcraft Computational Structural Dynamics (CSD, aka comprehensive) code such as CAMRAD or RCAS
  - The CSD code provides trim solution in addition to blade deformations
  - The interface to the CSD code is through standard OVERFLOW **`rotor_N.onerev.txt`** and **`motion.txt`** type files
  - Interface codes for CAMRAD are maintained and distributed by Doug Boyd, NASA Langley (contact d.d.boyd@nasa.gov)
  - RCAS coupling does not require any interface codes (RCAS API)
  - FUN3D has several postprocessing utility codes tailored to CAMRAD
- Coupled simulations are about as complicated as it gets with the basic FUN3D flow solver
  - There are *many* small details that must be done correctly; we don't have time to cover them all here

CFD/CSD – Loose (Periodic) Coupling

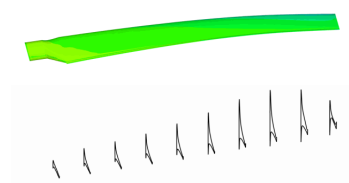
Coupling Process



CSD -> CFD



CFD -> CSD



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

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

Rotor-Specific Nondimensional Input (1/2)

- Typically define the flow reference state for rotors based on the tip speed; thus in **`rotor.input`**, set $\mathbf{U_{tip}/U_{ref}}$ **`= 1.0`** (data line 4)
- This way, $\mathbf{U_{inf}/U_{ref}}$ (data line 1) is equivalent to $\mathbf{U_{inf}/U_{tip}}$, 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 $L^*_{ref} = R^*$

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

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

Rotor-Specific Nondimensional Input (2/2)

- Nondimensional time step:

  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:

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

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

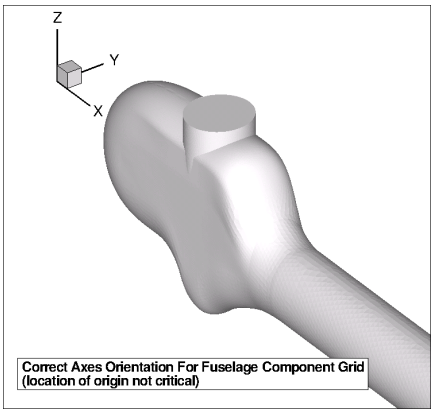
- Note: the azimuthal change per time step is output to the screen in the **`Rotor info`** section. Make sure this is consistent, to a high degree of precision (say at least 4 digits), with your choice of N steps per rev – you want the blade to end up very close to 360 deg. after multiple revs!
- Formulas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

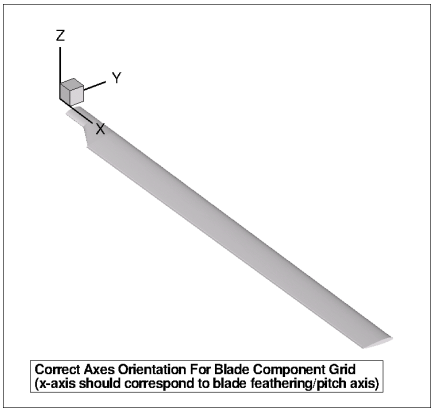
`dci_gen` Preprocessor (1/8)

- 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
  - 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 (2/8)

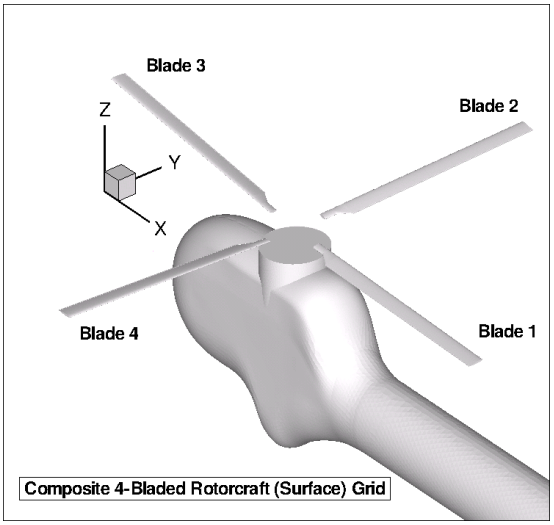
HART II *Component* Grids





`dci_gen` Preprocessor (3/8)

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
Required 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 13
- 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.
/
```

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 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

Blade Surface "Slicing"

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

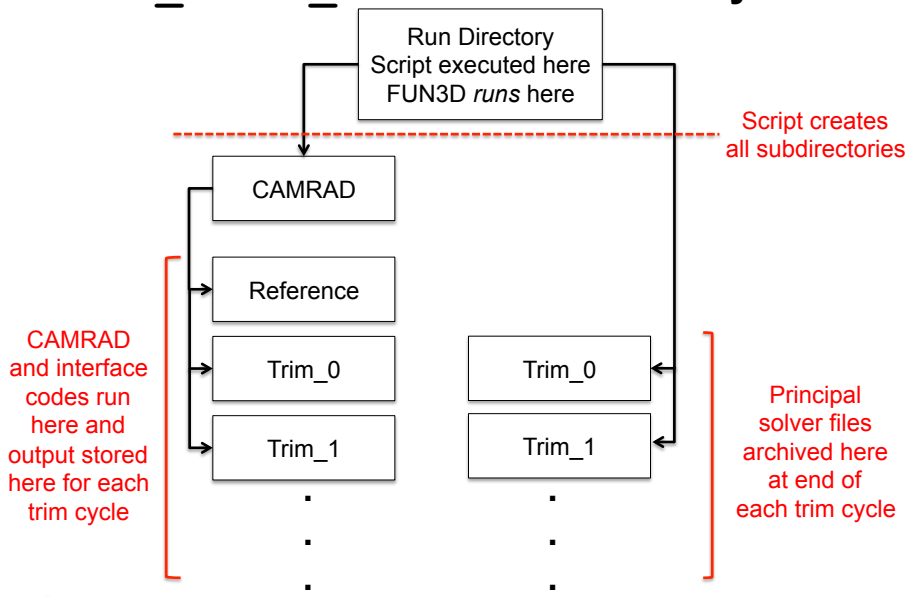
Untrimmed Rigid-Blade Simulations

- 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

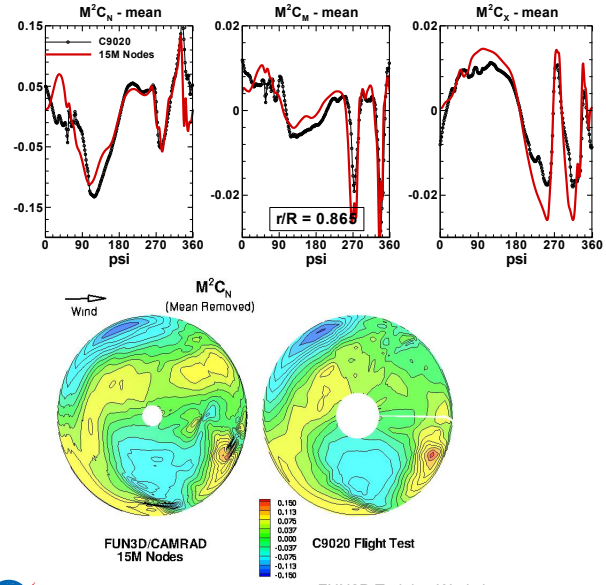
Trimmed, Elastic-Blade Simulations

- 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. Set up the 3 CAMRAD run-script templates
  7. 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
  8. 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
  9. Before using the run script make sure all items it needs are in place; script checks for missing items, but it gets old having to keep restarting because you forgot something!
  10. 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

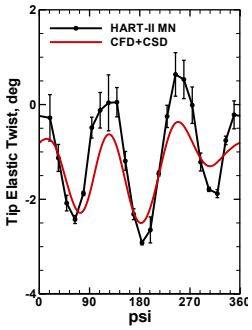
`RUN_LOOSE_COUPLING` Directory Tree



Postprocessing



Sample Plots Possible Via process_rotor_airloads.f90 Output



Non-Inertial 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 non-inertial 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 re-gridding
- The noninertial capability has other limited applications in addition to rotors – e.g. aircraft in a steady loop

Non-Inertial Reference Frame (2/2)

- **`fun3d.nml`** input for non-inertial 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_x   = 0.0
  rotation_rate_z   = 0.2
/
```

- The nondimensional rotation rate is determined as shown on slide 11
- Flow-visualization output (boundary, volume, sampling) will be relative to the non-inertial frame