AEROSTRUCTURAL RUNS with NSU3D

The master_nsu3d software pacakge is an extension of the NSU3D CFD code that enables coupled aerostructural analysis and design optimization applications. master_nsu3d is a driver code that calls specified disciplinary codes according to the specified RUN_TYPE. master_nsu3d requires its own input file, herein named input.master.* The input.master file is a FORTRAN namelist file, which specifies the RUN_TYPE and the input file names for each disciplinary code to be used in the simulation. For convenience, the disciplinary input files are generally kept in a spearate subdirectory herein named **./inputs** A simple example of the input.master file is given below:

```
!-------------------------------------------------------------------
! UCRM9 RIGID AERO
!-------------------------------------------------------------------
&control
!
RUN_TYPE       = 1000
NSU3D_INPUT_FILE = './inputs/input.nsu3d.fas'
!
&end
```

The **RUN_TYPE** in this example is set to **1000**, which specifies a standard CFD only run, i.e. rigid structure aerodynamic analysis. In this mode, master_nsu3d makes a single call to the NSU3D CFD flow solver, which runs in the same manner as if invoked directly as a stand-alone code. Here, only a single disciplinary input file is required, which is the **NSU3D_INPUT_FILE**. This corresponds to a standard input file for NSU3D as described in the NSU3D documentation.

An example of a multidisciplinary run input.master file is given below:

```
!-------------------------------------------------------------------
! UCRM9 FLEXIBLE AEROELASTIC
!-------------------------------------------------------------------
&control
!
RUN_TYPE       = 3000
NSU3D_INPUT_FILE = './inputs/input.nsu3d.cfdcsd'
CSD_INPUT_FILE = './inputs/input.csd.UCRM'
MM_INPUT_FILE = './inputs/input.meshmotion'
MM2D5_FSI_INPUT_FILE = './inputs/input.mm2d5.fsi'
!
&end
```

The **RUN_TYPE** in this example is set to **3000**, which specifies a coupled aerostructural analysis run. This involves multiple calls to NSU3D, the structural modeling code **AStrO**, the fluid-structure interface code, and the CFD mesh deformation code **MeshMotion**. Separate input files for each disciplinary code are specified in the input.master file. Nominally, the FSI code does not require an input file, although the **MM2D5.FSI** facility can be specified (as shown here) for producing smoother transfer of the computed structural displacements onto the surface CFD mesh for cases with significant mismatch between the outer mold lines of the CFD surface mesh and the CSD (computational structural dynamics) mesh.

Documentation for the individual disciplinary input files is provided below. As mentioned above, the NSU3D input file remains identical to that used for standalone NSU3D runs. However, additional optional parameters are required for coupled aerostructural runs. These include:

- **NCOUPLE_FSI**: The number of coupling cycles to be run. In each coupling cycle, the NSU3D flow solver is run according to the parameters set in the NSU3D input file, followed by the structural model, FSI, and mesh deformation code. Usually the number of coupling cycles can be in the range of 5 - 10. In this example, the number of coupling cycles is set to 25 in order to demonstrate complete convergence of the coupled aerostructural problem.

- **DYNPRESS_FSI**: This optional parameter specifies the dynamic pressure scaling to be applied to the loads that are transferred to the structural model from the CFD solution. Note that the CFD solution is typically computed in nondimensional units, whereas the structural model is run in dimensional units. Therefore, this parameter provides the conversion factor required for load transfer to the structural model. Note that the spatial dimensions (xyz coordinates) of the CFD and CSD codes must be consistent in any coupled aerostructural analysis run.
    - Example Calculation: In this case, the flow conditions are Mach = 0.85 at 37,000 ft altitude. At this altitude, we have the following properties:

      Air density = 0.3483 kg/m^3

      Air Temperature = 216.7 K

      Speed of sound = 295 m/sec

      The structural model is constructed in SI units. Therefore, the correct value of the **DYNPRESS_FSI** parameter correspnds to the dynamic pressure in SI units:

      DYNPRESS_FSI= 1/2 rho U^2 = 1/2 air_density (Mach * speed of sound)^2 = 10,955
- **RELAX_DX_FSI**: This parameter can be used to under-relax the aerodstructural coupling terms, by underelaxing the displacements produced by the CSD code applied to the CFD mesh. For flexible systems, this may be necessary to accelerate coupling convergence and to avoid excessive initial deflections.

Example Test Cases

The first two test cases are based on the uCRM9 aerostructural benchmark case. This case corresponds to the Undeflected Common Research Model (uCRM9) with a wing aspect ratio of 9. While the baseline CRM model geometry is a 1g in-flight model, the uCRM9 corresponds to the undeflected (jig-shape) geometry which has been designed to reproduce the 1g CRM geometry at the flow conditions corresponding to Mach = 0.85, CL=0.5 and 37,000 ft altitude. This is a benchmark aerostructural test case developed at the University of Michigan and documented at: https://mdolab.engin.umich.edu/wiki/ucrm

Test Case 1: uCRM9 Rigid Analysis

This case is archived in the RUN.1000 directory. The input.master file is reproduced below:

```
!-------------------------------------------------------------------
! UCRM9 RIGID AERO
!-------------------------------------------------------------------
&control
!
RUN_TYPE       = 1000
NSU3D_INPUT_FILE = './inputs/input.nsu3d.fas'
!
&end
```

Here, the **RUN_TYPE** is set to 1000, defining a standard CFD only run and the NSU3D_INPUT_FILE name is specified. Figure 1 depicts the convergence history of this standard steady-state CFD test case. The flow conditions for this case are Mach=0.85, 2 deg AOA, RE=40M. Note final CL value of 0.627.

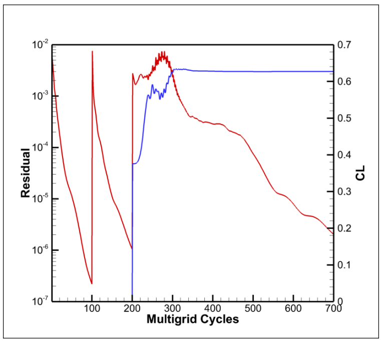

Figure 1: Convergence history of rigid (cfd alone) uCRM9 test case at Mach=0.85, 2 deg AOA, RE=40M. Note final CL value of 0.627.

Test Case 2: uCRM9 Aerostructural Analysis

This case is archived in the RUN.3000 directory.

```
!-------------------------------------------------------------------
! UCRM9 FLEXIBLE AEROELASTIC
!-------------------------------------------------------------------
&control
!
RUN_TYPE       = 3000
NSU3D_INPUT_FILE = './inputs/input.nsu3d.cfdcsd'
CSD_INPUT_FILE = './inputs/input.csd.UCRM'
MM_INPUT_FILE = './inputs/input.meshmotion'
MM2D5_FSI_INPUT_FILE = './inputs/input.mm2d5.fsi'
!
&end
```

Here, the **RUN_TYPE** is set to 3000, defining a coupled aerostructural analysis run. The required disciplinary input files are specified in the following lines. The NSU3D_INPUT_FILE includes the additional optional parameters **NCOUPLE_FSI**, **DYNPRESS_FSI** and **RELAX_DX_FSI**, as described previously. Note that the mesh sequence and number of cycles specified in the NSU3D_INPUT_FILE are executed each time the flow solver is called, at each coupling cycle. At each coupling cycle, the flow solver restarts with the flow solution computed at the end of the previous coupling cycle as the initial flowfield, with the exception of the first coupling cycle which is initialized in the usual manner (uniform freestream of restart file). For this reason it is advisable to provide a restart file/solution in the NSU3D_INPUT_FILE to be used in the first coupling cycle, as is done in this case. Here, the NSU3D_INPUT_FILE uses the solution computed in the previous example using **RUN_TYPE=1000**, which corresponds to the converged solution for a rigid structure, as shown in the first few lines from the NSU3D_INPUT_FILE:

```
uCRM9 AEROSTRUCTURAL ANALYSIS
RESTARTF  RESTARTT  RNTCYC
1.0        1.0       00.
RESTART FILE
WRK.rigid/restart.out
MMESH     NTHREAD
1.0       1.0              (1st order = -1)
```

```
NCYC       NPRNT      N MESH     MESHLEVEL    CFLMIN     RAMPCYC    TURBFREEZE    FVIS2  FSOLVER_TYPE
100.        0.0         4.         1.0         1.0        0.0         0.           0.       0.0
.
.
.
```

- **Positioning of CFD-CSD models:** Prior to running the full aerostructural simulation, it is useful to examine the model setup and in particular the relative positioning of the CFD and CSD (structural) models to ensure good performance of the FSI. At startup, the structural code interface writes out a file called **AStrO_baselinesurf.plt.n** that contains the surface faces of the structural model on processor "n". These files may be plotted along with the CFD surface mesh obtained from NSU3D to visualize the relative positioning of CFD and CSD meshes. Examples of these plots for this test case are shown below.

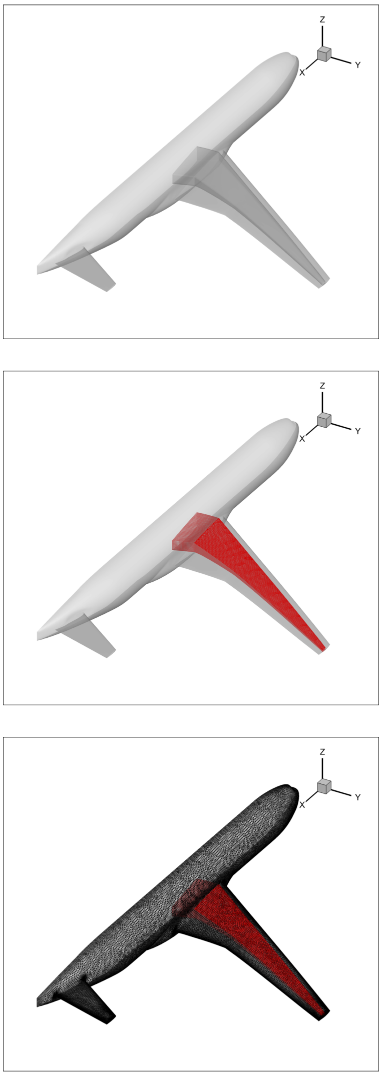

Figure 2: Overset plot of CFD surface mesh with CSD structural mesh for uCRM9 test case.

The CSD analysis is performed by assembling and directly inverting (or factorizing) the global stiffness matrix for the structure. This occurs on the first coupling cycle. Once the matrix has been factorized, it can be reused in subsequent coupling cycles, since the structural analysis problem is linear. Because the AStrO code currently runs on a single processor, for large structural models, the matrix factorization phase can be time consuming. Therefore, the factored matrix is output to a file named "ALTri.astro". On subsequent coupling cycles, if this file is available, it is read in and the matrix facorization stage is bypassed. The "ALTri.astro" file is specific and unique for a given structural model, and can thus be reused for various cases that employ the same structural model simply by copying the file to the run directory for that case.

Figure 3 compares the final converged aeroelastic solution with the rigid structure CFD solution, illustrating the wing deflection produced by the aerostructural interaction.

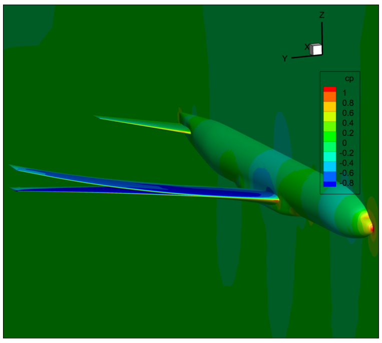

Figure 3: Comparison of rigid structure CFD solution with coupled aeroelastic flexible wing solution for uCRM9 test case at Mach=0.85, 2 deg AOA, Re=40M, at 37,000 ft altitude.

Figure 4 depicts the convergence history of the aerostructral case, starting from rigid CFD solution on the first coupling cycle, as explained above, and performing a total of 25 coupling cycles, each containing 100 multigrid cycles for the flow solver. The blue curve plots the convergence history of the lift coefficient, showing its variation at each coupling cycle. The initial CL value of 0.627, corresponding to that of the rigid structure, converges to a final value of 0.48 as the wing is deflected under the aerodynamic loading. Note that the coupled aerostructural problem is well converged for engineering purposes after less than 10 coupling cycles. However, the use of 25 coupling cycles demonstrates complete convergence of the coupled aeroelastic problem in this case.

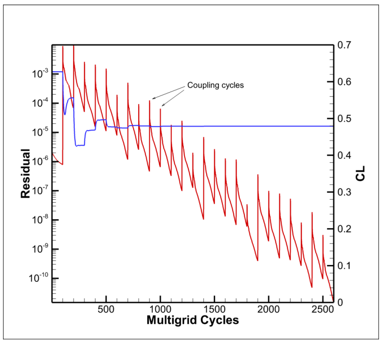

Figure 4: Convergence history of coupled aeroelastic problem showing complete convergence after 25 coupling cycles and convergence to engineering tolerances in less than 10 coupling cycles. Note final CL value of 0.48 versus starting rigid structure CL value of 0.627