NON INTERTIAL RUNS with NSU3D

Non-inertial runs make use of a moving reference frame in order to convert a time dependent problem into a steady-state problem. In most cases, this results in much faster time to solution since physical time stepping is not required. Obviously, not all time-dependent problems can be formulated this way and it is up to the user to formulate a proper non-inertial problem that admits a steady-state solution, otherwise the solution will not converge. Examples of non-inertial solutions include constant velocity translation of a body into a quiescent flow field, a constant pitch rate maneuver (or constant yaw rate or roll rate), and an isolated rotor in hover. Non-inertial reference frame problems can be combined with non-zero freestream conditions, for example to simulate an isolated spinning rotor in downward flow, although in many cases the addition of non-zero freestream conditions complicates or obviates the possibility of obtaining a steady-state solution.

Enabling non-inertial runs in the NSU3D input file:

For non-inertial runs, additional non-inertial parameters must be included in the NSU3D input file. These are placed after the **FORCE/MOMENT COEFFICIENT PARAMETERS** line and before the **MESH DATA FILE** line, using separation lines as shown below:

```
----------------------------------------------------------------------
FORCE/MOMENT COEFFICIENT PARAMETERS
REF_AREA  REF_LENGTH XMOMENT  YMOMENT   ZMOMENT  ISPAN   REF_MACH
858.3     16.5           0.0   0.0         0.0     3.0      0.64
----------------------------------------------------------------------
OPTIONAL NONINERTIAL PARAMETERS (MOVING GRID REFERENCE FRAME)
ROTATION
X0        Y0          Z0          OMEGAx    OMEGAy       OMEGAz
0.0       0.0         0.0          0.0        0.0        0.04563
TRANSLATION
XVEL      YVEL      ZVEL
0.0       0.0       0.0
--------------------------------------------------------------------
MESH DATA FILE
../grids/Hart2B_Rotor_C5_2.32Mn.part.320
----------------------------------------------------------------------
```

The key words **OPTIONAL NONINERTIAL** or **NONINERTIAL** are used to trigger reading of these parameters. Additonally, for backwards compatibility, the key words **OPTIONAL HOVER PARAMETERS** or **HOVER PARAMETERS** are also recognized for the same purpose.

There are two principal ways to specify non-inertial parameters. The first consists of specifying rotation and translation rates for the moving reference frame. In the second approach, nondimensional pitch, roll, and yaw rates are specified directly along with other flow parameters based on an aircraft coordinate system. These two approaches are described in detail below.

- **Specifying Rotation and Translation Rates**

```
----------------------------------------------------------------------
OPTIONAL NONINERTIAL PARAMETERS (MOVING GRID REFERENCE FRAME)
ROTATION
X0        Y0          Z0          OMEGAx    OMEGAy       OMEGAz
0.0       0.0         0.0          0.0        0.0        0.04563
TRANSLATION
XVEL      YVEL      ZVEL
0.0       0.0       0.0
--------------------------------------------------------------------
```

The above example shows a case where non-inertial rotation and translation rates are specified directly. These can be specified in any order, or either individually (i.e. rotation rate alone or only translation rate alone), where the default values are zero. These can be used in combination with far-field freestream flow values **MACH**, **Y-ANGLE**, **Z-ANGLE**, provided the resulting test case admits a steady-state solution.

- **Rotation rate specification parameters include**:
  - **X0, Y0, Z0**: Center of rotation coordinates
  - **OMEGAx, OMEGAy, OMEGAz**: Rotation rate vector, defines direction and magnitude (speed) of rotation.
- **Translation rate specification parameters include**:
  - **XVEL, YVEL, ZVEL**: Velocities in x-y-z directions respectively.

Rotational and translational velocities are nondimensional. The nondimensional values can be computed by matching a prescribed Mach number and noting that the freestream speed of sound in NSU3D is given as sqrt(gamma). Prescribing rotational rates from dimensional values may also require knowledge of the length scale of the CFD mesh. See the example descriptions under the **NSU3D Time Accurate Run** documentation.

- **Specifying Pitch/Yaw/Roll Rates**

```
----------------------------------------------------------------------
OPTIONAL NONINERTIAL PARAMETERS (MOVING GRID REFERENCE FRAME)
MACH     ALPHA      YAW
0.75      0.0       0.0
PITCH RATE
0.01
XBODY          YBODY       ZBODY
504.9           0.0         0.0
----------------------------------------------------------------------
```

The above example shows a case where non-inertial motion is defined in terms of Mach number, incidence and pitch rate. The parameters listed here are used to compute rotation and translation rates defined in the previous section internally by NSU3D, and the two methods are equivalent. However, the current approach enables the use of parmeters that are more familiar for aicraft motion/maneuvers.

- **Paramters include**:
  - **MACH, ALPHA, YAW**: These define the velocity vector of the body in the absence of any other freestream flow. If non-zero freestream flow conditions are specified in the NSU3D input file (in addition to these here), a non-zero freestream flow will be superimposed on the body motion.
  - **PITCH RATE**: Non-dimensional Pitch rate defined as qc/2V, where q=pitch rate, c=chord, V=aircraft speed
  - **YAW RATE**: Non-dimensional yaw rate defined as rb/2V, where r=yaw rate, b=span , V=aircraft speed
  - **ROLL RATE**: Non-dimensional roll rate defined as pb/2V, where p=roll rate, b=span , V=aircraft speed
  - **XBODY, YBODY, ZBODY**: Body center of rotation

Here we consider a specified pitch rate problem specification. These parameters are used to compute a center of rotation for the grid, and a rate of rotation which produces the prescribed Mach number and flow incidence at the XYZBODY location, with the given pitch rate. Note that for vanishingly small pitch rates, the grid center of rotation moves out to infinity. The implementation follows that described in: DOI: 10.2514/1.J051147

Example Test Cases

Test Case 1: Translation Only Steady Cruise Condition

In this test case we compare the steady-state static mesh solution with a non-inertial moving mesh in quiescent flow field solution for the F6 wing-body configuration at Mach=0.85 and 1 degree angle of attack.

The steady-state case uses the standard F6 test case input file with the specified far field flow conditions:

```
----------------------------------------------------------------------
MACH      Z-ANGLE   Y-ANGLE   RE       RE_LENGTH
0.85       0.00       1.0     3000000.    141.2
----------------------------------------------------------------------
FORCE/MOMENT COEFFICIENT PARAMETERS
REF_AREA  REF_LENGTH XMOMENT  YMOMENT   ZMOMENT  ISPAN     REF_MACH
72700.      141.2     504.9    0.0         0.0     2.0      0.85
----------------------------------------------------------------------
```

whereas the non-inertial case uses a zero freestream far field flow with non-inertial translational grid speeds:

```
----------------------------------------------------------------------
MACH      Z-ANGLE   Y-ANGLE   RE       RE_LENGTH
0.0        0.00       0.0     3000000.    141.2
----------------------------------------------------------------------
FORCE/MOMENT COEFFICIENT PARAMETERS
REF_AREA  REF_LENGTH XMOMENT  YMOMENT   ZMOMENT  ISPAN     REF_MACH
72700.      141.2     504.9    0.0         0.0     2.0      0.85
----------------------------------------------------------------------
OPTIONAL NONINERTIAL PARAMETERS (MOVING GRID REFERENCE FRAME)
TRANSLATION
XVEL         YVEL      ZVEL
-1.0055803   0.0       -0.0175525
----------------------------------------------------------------------
```

In this case the translation grid velocities corresponding to the above flow conditions are obtained as:

- XVEL = -MACH * sqrt(gamma) * cos (1 degree)
- ZVEL = -MACH * sqrt(gamma) * sin (1 degree)

where sqrt(gamma) is the freestream speed of sound in the NSU3D nondimensionalization, and the minus sign is due to the fact that the mesh motion is in the opposite direction of the resulting flow.

Figure 1.1 illustrates the convergence for steady-state case and the non-inertial translation case. The figure shows that the convergence history and final CL values are similar for both cases. However, these results are not identical for both cases because the flow field values and thus resulting discretizations are different for both cases. This can be seen in Figure 1.2, where the surface Mach number (and thus flow field velocities) on the body is zero for the steady-state case, whereas the surface Mach number is close to 0.85 on the non-inertial case (not exactly 0.85 due to variations in the local speed of sound).

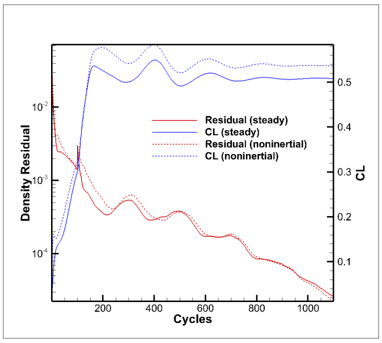


Figure 1.1: Convergence history for steady-state and non-inertial runs

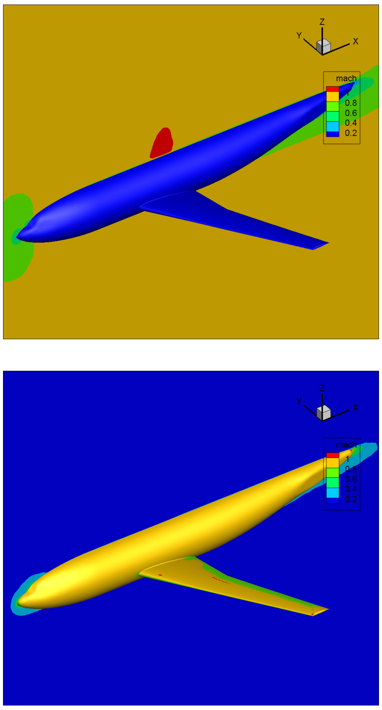
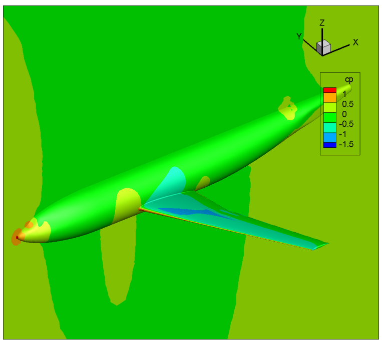


Figure 1.2: Computed local Mach number on body surface and symmetry plane for steady case (above/left) and noninertial case (below/right)

However, the pressure coefficient on the surface of the body is nearly identical in both cases, as shown in Figure 3.



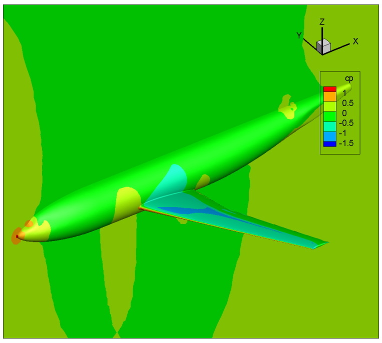


Figure 1.3: Computed local pressure coefficient on body surface and symmetry plane for steady case (above/left) and noninertial case (below/right)

Finally Figure 4 illustrates the density values on the surface, showing that substantial difference are observed between the two cases. This is due to non-enforcement of the adiabatic boundary condition in the non-inertial case.

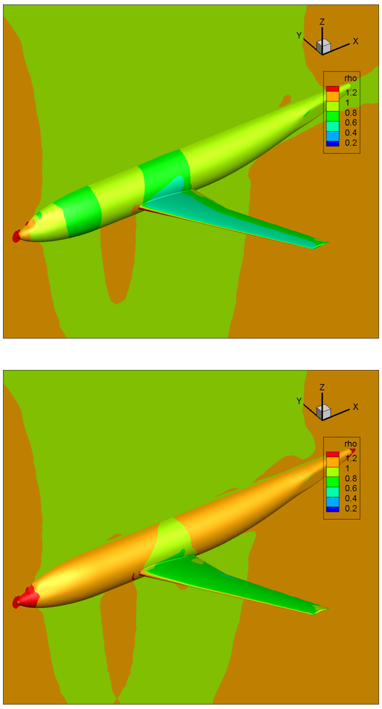


Figure 1.4: Computed local desnity on body surface and symmetry plane for steady case (above/left) and noninertial case (below/right)

Test Case 2: Constant Pitch Up Maneuver

In this test case we simulate a constant pitch rate maneuver for the F6 wind body configuration at Mach = 0.75 and 1 degree angle of attack. The freestream flow values are set to zero and the noninertial parameters are used to specify the pitch rate maneuver conditions. This includes the Mach number, angle of attack and pitch rate as shown below:

```
----------------------------------------------------------------------
MACH       Z-ANGLE   Y-ANGLE   RE        RE_LENGTH
```

```
0.0        0.00       0.0     3000000.    141.2
----------------------------------------------------------------------
FORCE/MOMENT COEFFICIENT PARAMETERS
REF_AREA  REF_LENGTH XMOMENT  YMOMENT   ZMOMENT  ISPAN     REF_MACH
72700.      141.2     504.9    0.0         0.0     2.0      0.75
----------------------------------------------------------------------
OPTIONAL NONINERTIAL PARAMETERS (MOVING GRID REFERENCE FRAME)
MACH     ALPHA(AOA) BETA(SIDESLIP)
0.75     1.0       0.0
PITCH RATE
0.01
XBODY         YBODY       ZBODY
504.9          0.0         0.0
----------------------------------------------------------------------
```

This represents an alternate way of specifying non-inertial parameters in terms of typical aircraft parameters. These parameters are used to compute the translation and rotation non-inertial parameters that produce the corresponding pitch rate and freestream conditions. These parameters are output by NSU3D at startup in the std output file as shown below:

```
==========================================================================================
------------------------------------------------------------------------------------------
NONINERTIAL PARAMETERS DERIVED FROM PITCH/YAW/ROLL RATES:
ROTATION
   XROT           YROT           ZROT           OMEGAX         OMEGAY         OMEGAZ
   0.381686E+03   0.000000E+00   0.705892E+04   0.000000E+00   0.125696E-03   0.000000E+00
TRANSLATION
   XGVELTRANS     YGVELTRANS     ZGVELTRANS
   0.000000E+00   0.000000E+00   0.000000E+00
------------------------------------------------------------------------------------------
==========================================================================================
```

Note that if these translation and rotation parameters are specified in the input file in the place of the pitch rate parameters, the identical simulation will be produced. A pitch rate specification corresponds to a pure rotation about the span axis as shown above. As the pitch rate becomes smaller, the center of rotation moves further away from the body. When the pitch rate is set to zero (q=0.0), the center of rotation moves to infinity. To avoid this singularity, the noninertial motion switches to a pure translation specification for zero pitch/roll/yaw rates. As an example, the zero pitch rate case can be prescribed as follows in the NSU3D input file:

```
----------------------------------------------------------------------
MACH      Z-ANGLE   Y-ANGLE   RE       RE_LENGTH
0.0        0.00       0.0     3000000.    141.2
----------------------------------------------------------------------
FORCE/MOMENT COEFFICIENT PARAMETERS
REF_AREA  REF_LENGTH XMOMENT  YMOMENT   ZMOMENT  ISPAN     REF_MACH
72700.      141.2     504.9    0.0         0.0     2.0      0.75
----------------------------------------------------------------------
OPTIONAL NONINERTIAL PARAMETERS (MOVING GRID REFERENCE FRAME)
MACH     ALPHA(AOA) BETA(SIDESLIP)
0.75     1.0       0.0
PITCH RATE
0.0
XBODY         YBODY       ZBODY
504.9          0.0         0.0
----------------------------------------------------------------------
```

resulting in the following noninertial parameters (determined internally by NSU3D and output to stdout):

```
==========================================================================================
------------------------------------------------------------------------------------------
NONINERTIAL PARAMETERS DERIVED FROM PITCH/YAW/ROLL RATES:
ROTATION
   XROT           YROT           ZROT           OMEGAX         OMEGAY         OMEGAZ
   0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00
TRANSLATION
   XGVELTRANS     YGVELTRANS     ZGVELTRANS
  -0.887277E+00   0.000000E+00  -0.154875E-01
------------------------------------------------------------------------------------------
==========================================================================================
```

In this test case, the F6 wing body is first simulated at a pitch rate of q=0.01 with Mach=0.75 at 0 and 1 degree angles of attack. Next the same case is simulated for Mach=0.75, Incidence=1 degree, for 4 values of the pitch rate: q = 0.0, q = 0.0001, q = 0.01 and q = 0.02

Figure 2.1 illustrates the convergence history for q=0.01 case at 0 degrees and 1 degree angle of attack with Mach=0.75. As can be seen, the residual histories are similar, and the higher angle of attack produces a higher CL value as expected.

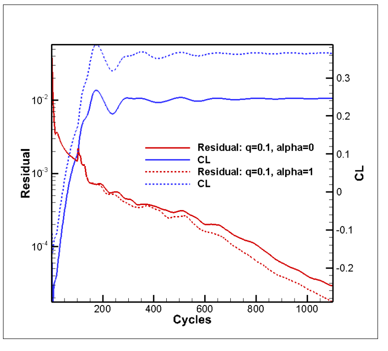


Figure 2.1: Convergence history for q=0.01 pitch up maneuvers at 0 and 1 degree angle of attack.

Figure 2.2 illustrates the convergence histories for the different pich rate values at Mach=0.75 and 1 degree angle of attack. The residual convergence histories are similar for all pitch rates. However, the CL value is seen to decrease significantly with increasing pitch rate. As expected, the solution at q=0.0001 is very close to the vanishing pitch rate solution (no rotation).

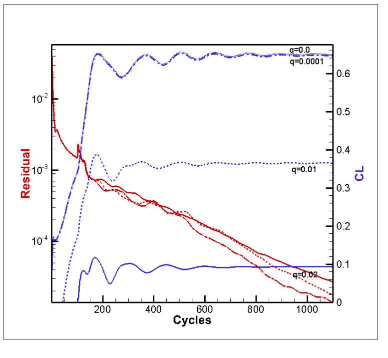


Figure 2.2: Convergence history for various pitch rates at 1 degree angle of attack.

Figure 2.3 depicts the grid speeds applied by the noninertial case for three pitch rate values, q = 0.0001, q = 0.01, and q = 0.02. Note the increasing rotational motion of the grid observed as the pitch rate is increased.

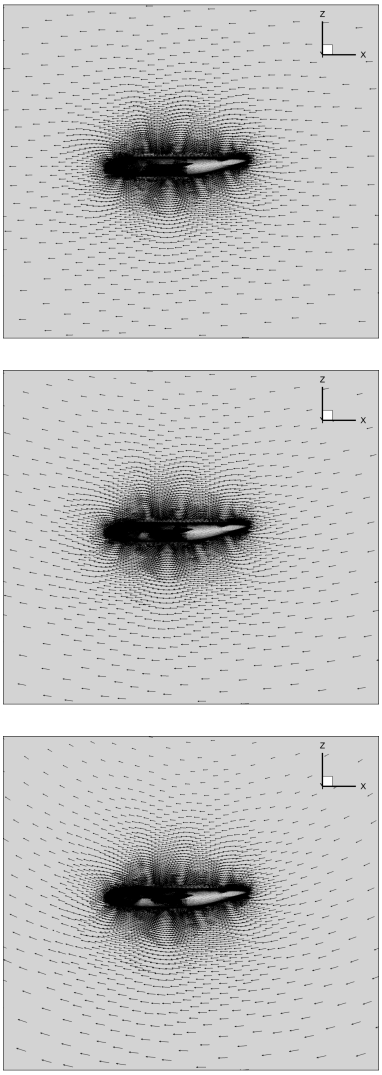
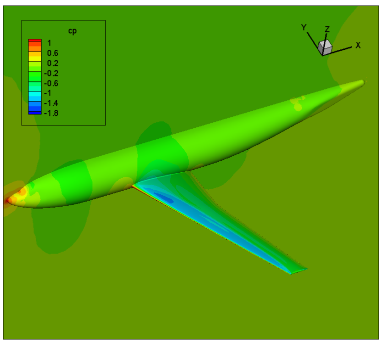


Figure 2.3: Grid speeds for q=0.0001, q=0.01 and q=0.02 pitch rates at 1 degree angle of attack.

Figure 2.4 plots the computed surface pressure coefficient for pitch rate values q = 0.0 (similar to q = 0.0001), q = 0.01 and q = 0.02. As expected, the suction peaks on the wing diminish in magnitude with increasing pitch rate, leading to lower CL values.



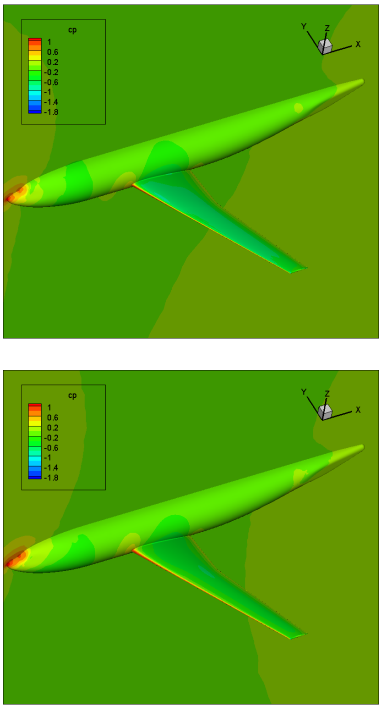


Figure 2.4: Surface pressure distributions for q=0.0, q=0.01 and q=0.02 pitch rates at 1 degree angle of attack.

Test Case 3: Isolated Rotor in Hover

This test case consists of an isolated four-bladed rotor in hover with a blade tip Mach number of approximately 0.64. This is the HART 2 rotor configuration, with the mesh nondimensionalized by the blade chord. A zero freestream Mach number is specified, and the noninertial parameters consist of pure rotationabout the Z axis (azimuith of rotor):

```
----------------------------------------------------------------------
MACH      Z-ANGLE    Y-ANGLE   RE        RE_LENGTH
0.0       0.0        0.0      2.147678e+06     1.0
----------------------------------------------------------------------
FORCE/MOMENT COEFFICIENT PARAMETERS
REF_AREA   REF_LENGTH XMOMENT   YMOMENT    ZMOMENT  ISPAN    REF_MACH
858.3      16.52893      0.0    0.0         0.0      2.0       0.637554652817
----------------------------------------------------------------------
OPTIONAL NONINERTIAL PARAMETERS (MOVING GRID REFERENCE FRAME)
ROTATION
X0        Y0          Z0          OMEGAx     OMEGAy       OMEGAz
0.0       0.0         0.0          0.0        0.0          0.0456389419788
----------------------------------------------------------------------
```

Figure 3.1 illustrates the convergence in terms of residual and CZ (proportional to thrust coefficient) and CMZ (proportional to torque coefficient) for this case.

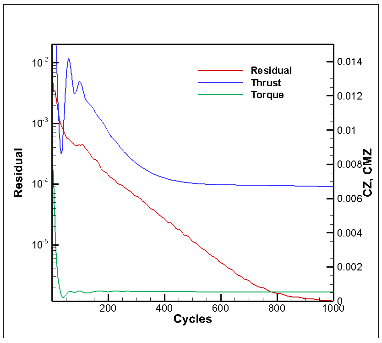


Figure 3.1: Convergence history for HART2 rotor in hover with tip Mach number = 0.64.

Figure 3.2 depicts the flow field computed for the isolated rotor in hover test case run in noninertial mode. These results can be compared with those obtained in the time dependent simulation of the same test case where they are seen to be in close agreement.

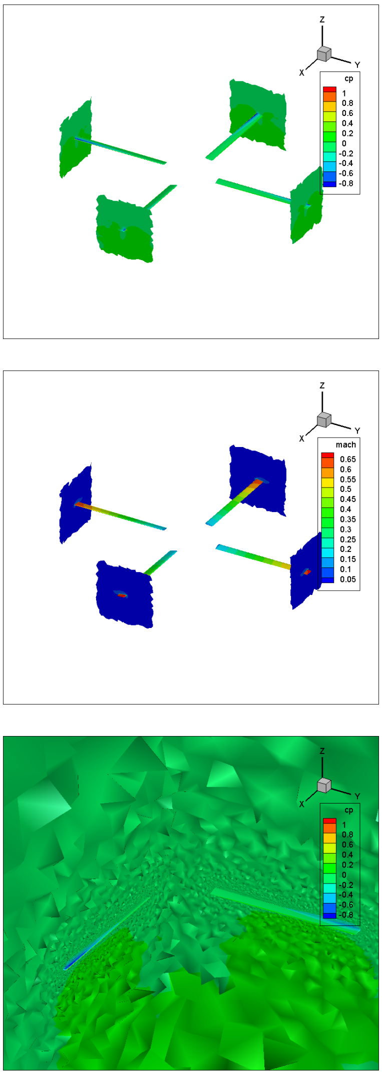


Figure 3.2: Flow field solution for HART2 rotor in hover with tip Mach number = 0.64.

Note for this case a non-zero freestream along the Z axis can be prescribed in addition to the non-inertial motion while still admitting a steady-state solution. For example, an ascending rotor can be simulated by prescribing a non-zero Mach number (Mach = 0.1 for example) and a Y-angle of -90 degrees.