"XTurb"

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Sikorsky S-76 Helicopter & REpower 5-MW Wind Turbine

http://www.rotoraero.psu.edu/

Online Graduate Certificate in Wind Energy

9-Credit Online Certificate

(can also take one or two courses)

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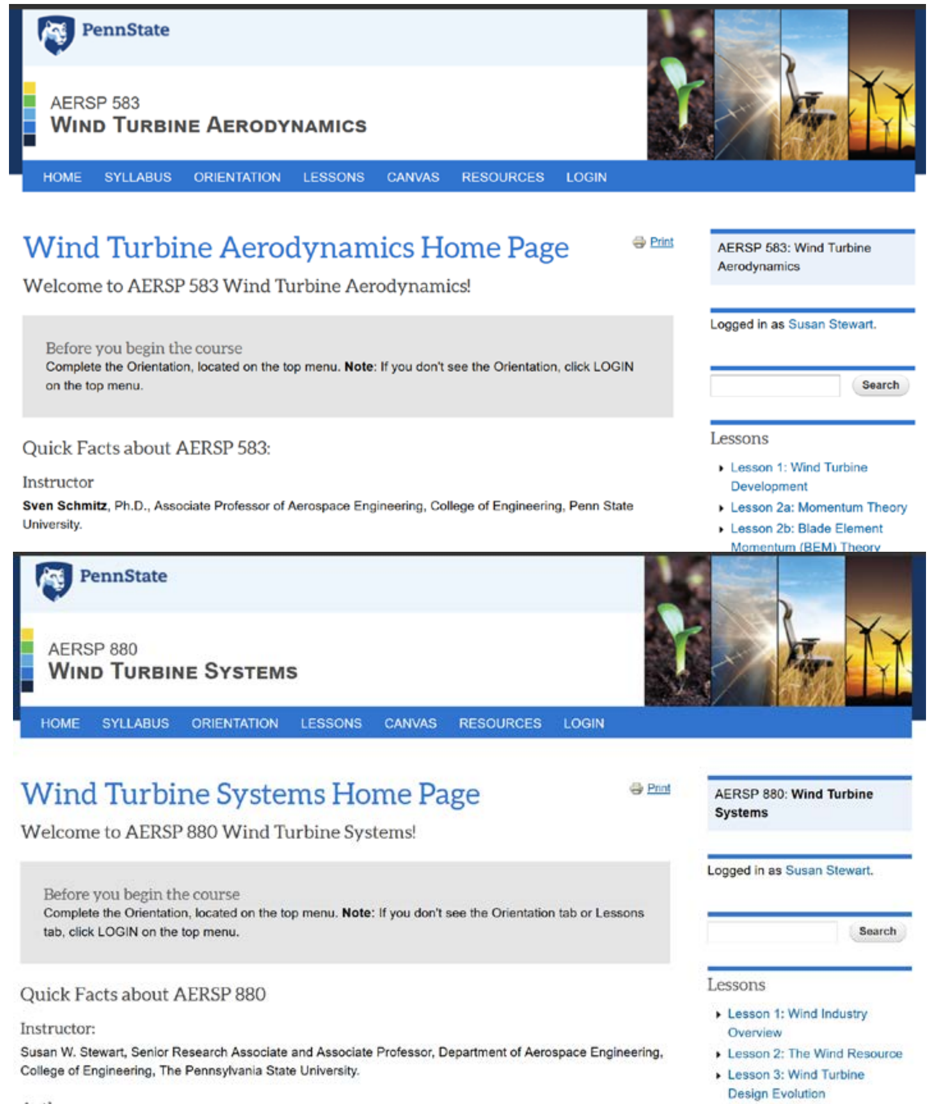
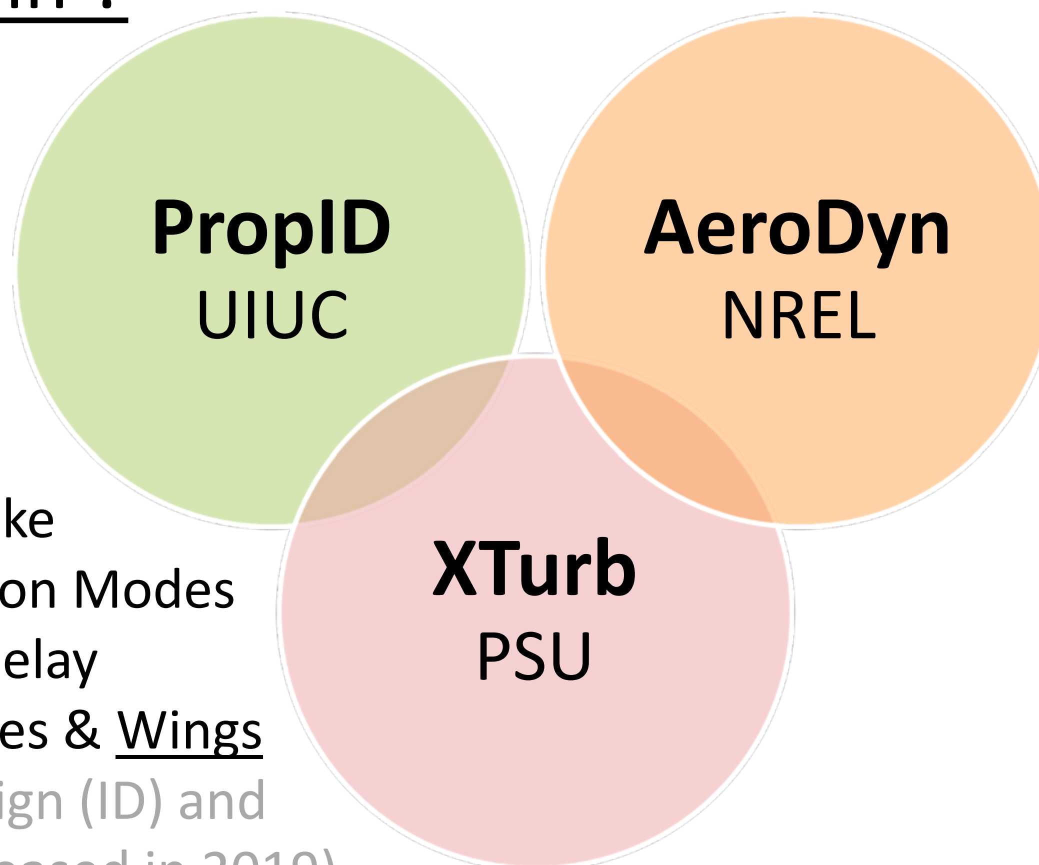
- **Wind Turbine Aerodynamics**
  AERSP 583
- **Wind Turbine Systems**
  AERSP 880
- **Engineering of Wind Project Development**
  AERSP 886

See overview video at
https://www.youtube.com/watch?v=zm39hEEyw6o



"XTurb"

- <u>Where does XTurb fit in ?</u>
  - Aerodynamics <u>only</u> !
  - Bridging capabilities of PropID & AeroDyn
  - Selected Features :
    - <u>Two Models :</u> BEMT & Prescribed Wake
    - Design/Analysis/Prediction Modes
    - Built-In Viterna & Stall-Delay
    - Analysis of 'Parked' Blades & <u>Wings</u>
    - Constrained Inverse Design (ID) and Optimization (to be released in 2019)



XTurb References

XTurb

Schmitz S (2012) XTurb-PSU: a wind turbine design and analysis tool. http://www.aero.psu.edu/Faculty_Staff/schmitz/XTurb/XTurb.html.

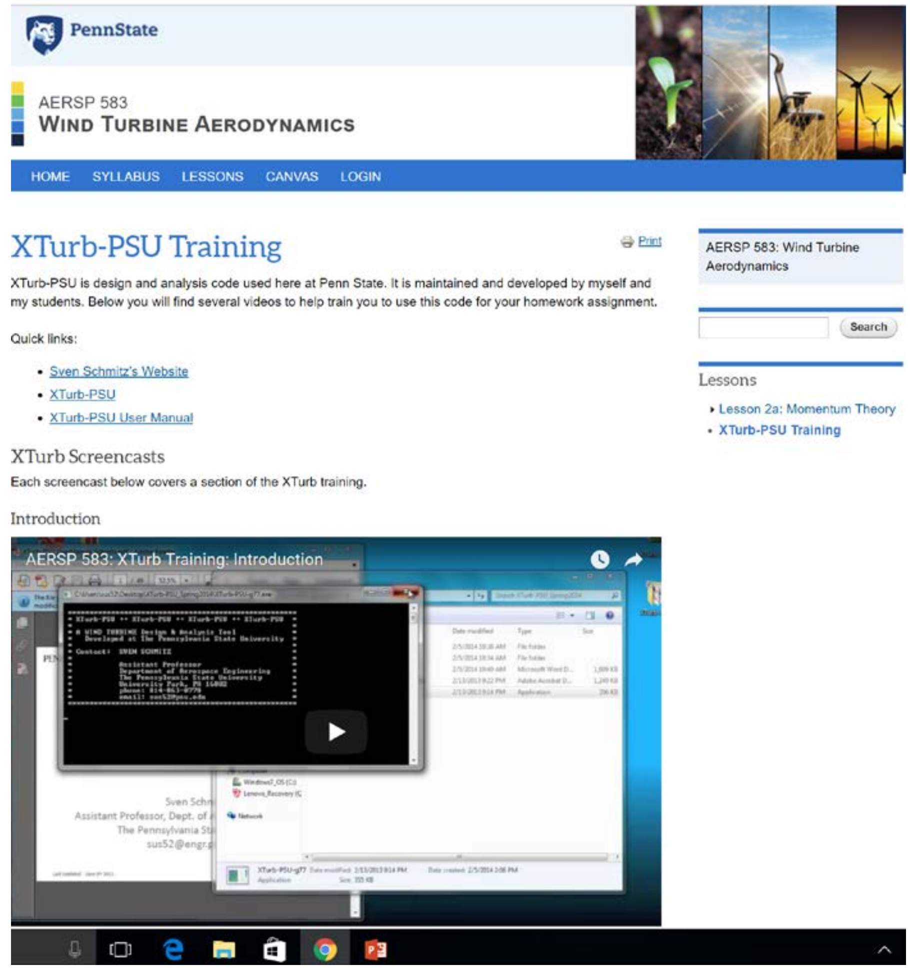
PSU Generic 1.5-MW Turbine

Schmitz S (2015) PSU Generic 1.5-MW Turbine. https://www.researchgate.net/publication/314209269_PSU_Generic_15-MW_Turbine?channel=doi&linkId=58b9fe7ea6fdcc2d14de3602&showFulltext=true

DOI: 10.13140/RG.2.2.22492.18567.

Please cite references when used for research & teaching.

XTurb Training Videos



https://www.e-education.psu.edu/aersp583/node/583

- On the horizon …
  - Text on Wind Turbine Aerodynamics
  - Approx. 250 pages
  - XTurb input decks for wind turbines across scales (accompanying website)
  - Blade-Element Momentum & Vortex Theory, Advanced Tip Modeling, Solution-Based Stall Delay
  - Chapters on Aerodynamic Theory, Wind Resource, Inverse Design & Optimization, Scaled Wind Turbine Design, Wind Turbine Airfoils, Introd. To Unsteady Aerodynamics, Iced Airfoil Aerodynamics, …

John Wiley & Sons, Ltd

And

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Book Manuscript

Aerodynamics of Wind Turbines: A Physical Basis for Analysis and Design

To be published: ***Fall 2019***

WILEY

PennState
College of Engineering

“XTurb”

Manual

Table of Content

- Getting Started
- Input Modules
  - Blade (Geometric Definitions)
  - Operation (Design, Analysis, Prediction)
  - Solver (Solver & Grid Selection)
  - HVM (Helicoidal Vortex Method)
  - BEMT (Blade Element Momentum Theory)
- Output Files
  - General & Method Specific Output

Getting Started

- Extract Files from XTurb_V#.#.tar

```
tar -xvf  XTurb_V#.#.tar
```

- Run Directory

```
cd XTurb_V#.#/Example_1
```

- Executable

Spring 2014 version used in AERSP 583
New release (g95) coming in 2019

```
../src/XTurb-PSU-g77.exe < ex1.inp
```

Getting Started

- Executable

  You can also use … ‘nohup’

```
/usr/bin/nohup ../src/XTurb-g77**.exe < test1.inp > nohup.out
```

  This will re-direct all screen output to nohup.out.

- Operating Systems
  - Unix/Linux
  - Windows + Cygwin (recommended)
  - Windows Command Prompt

Input Modules

- Structure of Input File

&BLADE … &END	**Geometric Definitions**
&OPERATION … &END	**Design, Analysis, Prediction**
&SOLVER … &END	**Solver & Grid Selection**
&HVM … &END	**Helicoidal Vortex Method**
&BEMT … &END	**Blade Element Momentum Theory**

Input Modules

- Inputs - BLADE

```
&BLADE
    Name        = 'NREL-PhaseVI',      Design Name

    BN          = 2,                   Blade Number

    ROOT        = 0.25,                Root Location / Radius


    NTAPER      = 2,                   # Chord Definitions

    RTAPER      = 0.25,                Radial Location / Radius
                  1.00,

    CTAPER      = 0.1465,              Blade Chord / Radius
                  0.0707,
&END
```

Input Modules

- Inputs - BLADE

```
&BLADE
    NTWIST      = 20,           # Twist Definitions

    RTWIST      = 0.250,        Radial Location / Radius
                  0.267,
                    …
                  1.000,

     DTWIST     = 20.040,       Twist Angle [deg]
                  18.074,
                    …
                  -1.816,

      NAIRF     = 2,            # Airfoil Polars
&END
```

Input Modules

- Inputs - BLADE

```
&BLADE
    RAIRF    = 0.25,                        Radial Location / Radius
               0.50,

    AIRFDATA = './S809_Re6E5.dat',          Path to XFOIL Polar
               './S809_Re1E6.dat',

      NSWEEP   = 2,                         # Sweep Definitions

      RSWEEP   = 0.25,                      Radial Location / Radius
                 1.00,

      LSWEEP   = 0.00,                      Blade Sweep / Radius
                 0.00,
&END
```

Input Modules

- Inputs - BLADE Example : XFOIL Polar

```
      XFOIL         Version 6.8

Calculated polar for: 1.     0.

1 1 Reynolds number fixed          Mach number fixed

xtrf =   1.000 (top)        1.000 (bottom)
Mach =   0.000     Re =     0.500 e 6     Ncrit =   9.000

  alpha     CL        CD       CDp       CM     Top Xtr  Bot Xtr
 ------- -------- --------- --------- -------- -------- --------
  0.000   0.1452   0.01352   0.00682  -0.0431   0.6141   0.5406
  0.500   0.2046   0.01361   0.00689  -0.0447   0.6125   0.5425
  1.000   0.2633   0.01357   0.00696  -0.0461   0.6108   0.5449
  1.500   0.3223   0.01364   0.00715  -0.0474   0.6093   0.5471
      …              …              …              …
```

Input Modules

- Inputs - BLADE

```
&BLADE
      NDIHED    = 2,              # Dihedral Definitions
      RDIHED    = 0.25,           Radial Location / Radius
                  1.00,

      LDIHED    = 0.00,           Blade Dihedral / Radius
                  0.00,

      NTWAX     = 2,              # Twist Axis Definitions

      RTWAX     = 0.25,           Radial Location / Radius
                  1.00,

      LTWAX     = 0.30,           Twist Axis / Chord
                  0.30,
&END
```

Input Modules

- Inputs - BLADE

```
&BLADE
        NPIAX     = 2,                  # Pitch Axis Definitions
        RPIAX     = 0.25,               Radial Location / Radius
                    1.00,

        LPIAX     = 0.30,               Pitch Axis / Chord
                    0.30,
&END
```

Note that in current version …

1. No Sweep & Dihedral (BEMT); No Dihedral (HVM)
2. No usage of NTWAX, RTWAX, LTWAX and NPIAX, RPIAX, LPIAX

Input Modules

- Inputs - BLADE

&BLADE

VITERNA = 0,	**No correction to Airfoil Data**
VITERNA = 1,	**Applies VITERNA extrapolation to Airfoil Data at every radial station**
BLENDAIRF = 0,	**No blending of Airfoil Data**
BLENDAIRF = 1,	**Blending of Airfoil Data around airfoil breakpoints**
PERCENTR = 5,	**Percentage [%] of blade radius around airfoil breakpoints where blending is active** - only with BLENDAIRF = 1

&END

Input Modules

- Inputs - BLADE

&BLADE

STALLDELAY = 0,	**NO modification of Airfoil Data**
STALLDELAY = 1,	**Stall-Delay Model -> 3-D Effects on Airfoil Data** - Selig & Du (Lift Coefficient) - Eggers (Drag Coefficient) ⇔ **AirfoilPrep (NREL)**
STALLDELAY = 2,	**Solution-Based Stall-Delay Model** - Dowler & Schmitz [Wind Energy, 2014] - <u>Only for BEMT, i.e. METHOD = 1</u>

&END

Input Modules

- Structure of Input File

&BLADE … &END	Geometric Definitions
&OPERATION … &END	Design, Analysis, Prediction
&SOLVER … &END	Solver & Grid Selection
&HVM … &END	Helicoidal Vortex Method
&BEMT … &END	Blade Element Momentum Theory

Input Modules

- Inputs - OPERATION

```
&OPERATION
     CHECK    = 1,
&END
```

The CHECK Setting …

```
CHECK    = 1,
```

- Recommended before actual computation
- Review input parameters and solver settings

```
CHECK    = 0,
```

- Proceeds directly to computation

Input Modules

- The CHECK Setting (What to look for …)

```
****************************************************
*                 AIRFOIL DATA                     *
****************************************************

***** Airfoil Polars  NAIRF      =  2  *****

*** Polar # 1 ***
  r/R     File
  0.2500 ./S809_Re6E5.dat

  From     To      (r/R)
  0.2500   0.500

+++++ Extrema of Cl vs. alpha +++++

     Extremum = 29  CL = 1.0733
     Extremum = 31  CL = 1.0709
     Extremum = 39  CL = 1.0958

 Number AOA[deg] CL        CD        CDP       CM
---------------------------------------------------
    1   0.0000   0.1452   0.0135   0.0068  -0.0431
    2   0.5000   0.2046   0.0136   0.0069  -0.0447
    3   1.0000   0.2633   0.0136   0.0070  -0.0461
          …         …         …         …         …
```

Input Modules

- The CHECK Setting (What could happen …)

```
+++++ Extrema of Cl vs. alpha +++++

     Extremum = 29  CL = 1.0733
     Extremum = 31  CL = 1.0709
     Extremum = 39  CL = 1.0958
     Extremum = 51  CL = 1.53493285
     Extremum = 55  CL = -1.43988514
     Extremum = 59  CL = 1.30977213

 Data Distribution NOT favorable !
 Curvature change in CD vs. CL at single data point
  Suggest adding/interpolating a new data point
  ... between 52 and 53 i.e. AOA = 0.275000006 deg and AOA =
0.349999994 deg

 Data Distribution NOT favorable !
 Curvature change in CD vs. CL at single data point
  Suggest adding/interpolating a new data point
  ... between 58 and 59 i.e. AOA = 0.725000024 deg and AOA =
0.800000012 deg

  Number AOA[deg] CL        CD        CDP       CM
 ---------------------------------------------------
     1    0.0000   0.1452   0.0135   0.0068  -0.0431
     2    0.5000   0.2046   0.0136   0.0069  -0.0447
             …         …         …         …         …
```

If you repair the polar file manually, you get the OK as on the previous slide.

Input Modules

- The CHECK Setting (What to look for …)

```
*****************************************************
*            RADIAL DISTRIBUTION - INPUT            *
*****************************************************

Using a COSINE distribution from root to tip ...

Input Data interpolated to radial stations r(j)

 Number r/R     Chord/R Twist[deg] Sweep/R  Dihed/R  Polar #
-------------------------------------------------------------
    1   0.2500   0.1465  20.0400   0.0000   0.0000     1
    2   0.2512   0.1464  19.9063   0.0000   0.0000     1
    3   0.2546   0.1460  19.5061   0.0000   0.0000     1
    4   0.2604   0.1455  18.8417   0.0000   0.0000     1
    5   0.2684   0.1446  17.9188   0.0000   0.0000     1
    6   0.2785   0.1436  16.7509   0.0000   0.0000     1
        …        …        …        …        …        …
```

Check that inputs transfer to computational grid

Input Modules

- Inputs - OPERATION

&OPERATION	
`DESIGN = 1,`	**"Design" Mode**
`NTSR = 10,`	**# Tip Speed Ratios, TSR**
`BTSR = 2,`	**Minimum TSR**
`ETSR = 20,`	**Maximum TSR**
`NPITCH = 2,`	**# Blade Pitch Angles**
`BPITCH = 1.8,`	**Minimum Pitch Angle [deg]**
`EPITCH = 3.0,`	**Maximum Pitch Angle [deg]**
&END	

Input Modules

- Inputs - OPERATION - Design (Screen Output)

```
Total of NTSR * NPITCH = 20 cases.

 +++++++ The following cases will be computed. +++++++

    Number    TSR        PITCH [deg]
         1    2.0000     1.8000
         2    4.0000     1.8000
         3    6.0000     1.8000
              …      …      …
        11    2.0000     3.0000
        12    4.0000     3.0000
        13    6.0000     3.0000
              …      …      …
 +++++++++++++++++++++++++++++++++++++++++++++++++++++
```

Input Modules

- Inputs - OPERATION

&OPERATION	
ANALYSIS = 1,	**"Analysis" Mode**
NANA = 10,	**# Blade Analysis Cases**
TSRANA = 2,	**Minimum TSR**
4,	**…**
...	**…**
20,	**Maximum TSR**
PITCHANA = 3.0,	**Minimum Pitch Angle [deg]**
3.0,	**…**
...	**…**
3.0,	**Maximum Pitch Angle [deg]**
&END	

Input Modules

- Inputs - OPERATION - Analysis (Screen Output)

```
Total of NANA = 10 cases.

+++++++ The following cases will be computed. +++++++

  Number    TSR        PITCH [deg]
       1    2.0000    3.0000
       2    4.0000    3.0000
       3    6.0000    3.0000
       4    8.0000    3.0000
       5   10.0000    3.0000
       6   12.0000    3.0000
       7   14.0000    3.0000
       8   16.0000    3.0000
       9   18.0000    3.0000
      10   20.0000    3.0000
+++++++++++++++++++++++++++++++++++++++++++++++++++++
```

Input Modules

- Inputs - OPERATION

&OPERATION	
PREDICTION = 1,	**“Prediction” Mode**
BRADIUS = 5.03,	**Blade Radius [m]**
RHOAIR = 1.225,	**Air Density [kg/m^3]**
MUAIR = 1.8E-05,	**Air Dynamic Visc. [kg/(m*s)]**
NPRE = 2,	**# Prediction Cases**
&END	

Input Modules

- Inputs - OPERATION

```
&OPERATION

      VWIND    = 5.0,              Wind Speed [m/s]
                 7.0,

      RPMPRE   = 72.0,             Rotor RPM
                 72.0,

      PITCHPRE = 3.0,              Blade Pitch Angle [deg]
                 3.0,
&END
```

Input Modules

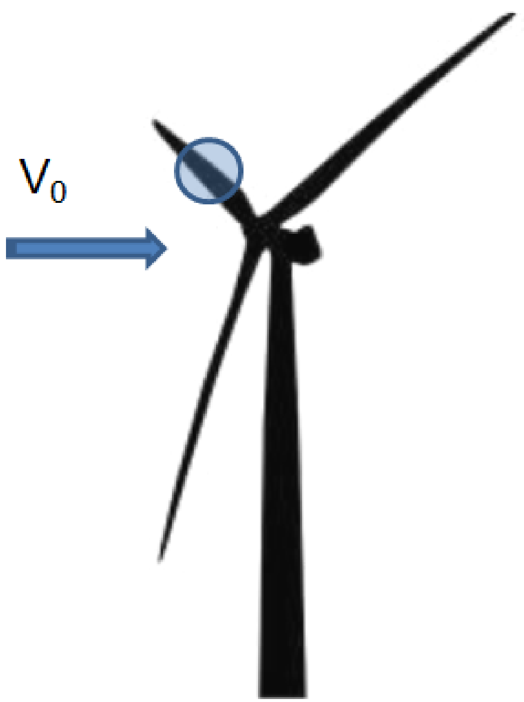
- Inputs - OPERATION - Prediction (Screen Output)

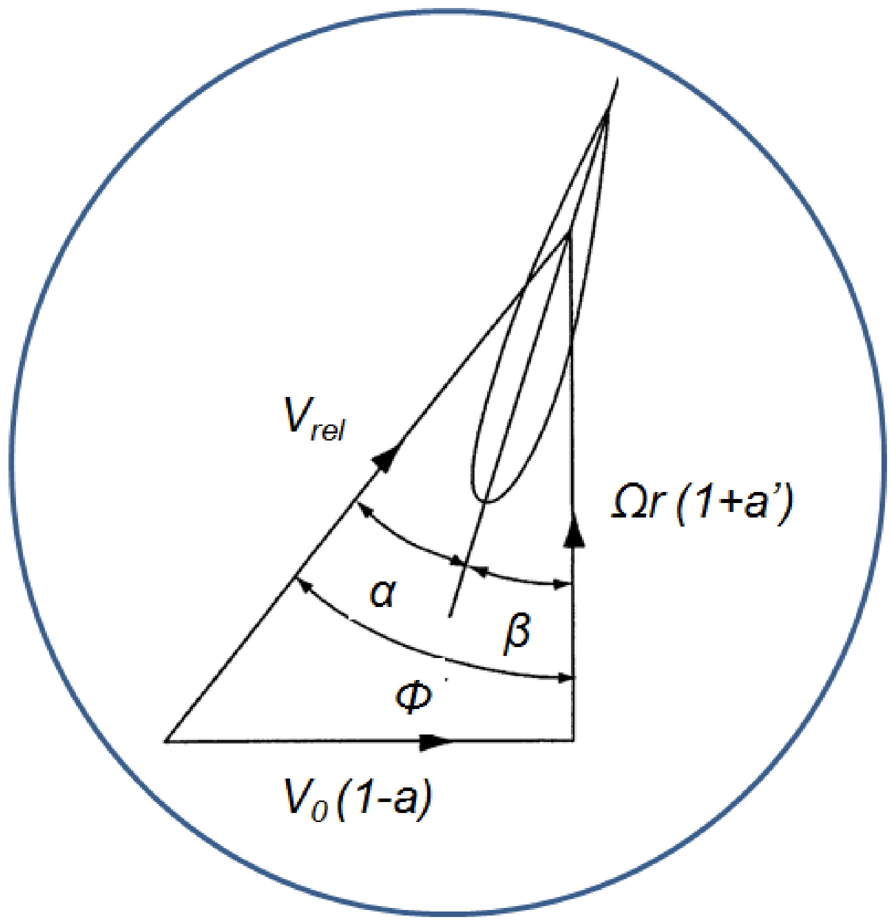
```
Total of NPRE = 2 cases.

 +++++++ The following cases will be computed. +++++++

 Equation :  TSR = (Omega*BRADIUS)/VWIND
                 = (2*pi/60*RPM*BRADIUS)/VWIND

   Number   TSR       PITCH [deg]
        1   7.5851    3.0000
        2   5.4179    3.0000

 +++++++++++++++++++++++++++++++++++++++++++++++++++++
```

XTurb translates into TSR & PITCH.

Input Modules

- How is PITCH [deg] defined … ?





Input Modules

- How is PITCH [deg] defined … ?
  - Φ = Local Flow Angle = $\alpha + \beta$
  - α = Local Angle of Attack
  - β = 'Total' Local Twist

    = DTWIST + (PITCH – $DTWIST_{Tip}$)

- Therefore, PITCH = β_{Tip}

Input Modules

- Wind Turbine
  - Positive Twist = Nose Down
  - PITCH = β_{Tip}

- Rotorcraft
  - Positive Twist = Nose Up
  - PITCH = $\beta_{r/R=0.75}$

- The ‘Schmitz’ Rule says :

“Positive Twist means Nose into the Wind. – Always.”

Input Modules

- How is PITCH [deg] defined ... ? (Screen Output)

```
*****************************************************
*    +++ SOLUTION +++ SOLUTION +++ SOLUTION +++     *
*****************************************************


++++++++++ NEW CASE +++++++++++
  Number    TSR       PITCH [deg]
       1    7.5851    3.0000

Non-Dimensionalization :
 Length Scales     => Blade Radius   BRADIUS
 Velocity Scales   => Wind Speed     VWIND

 In other words ... BRADIUS = VWIND = 1.00

Modifying Blade Twist from INPUT :
 Adding 4.816 deg to get Tip Pitch Angle of 3. deg
```

Input Modules

- How is PITCH [deg] defined … ? (Screen Output)

```
 Number    r/R     Twist[deg]
------------------------------
      1   0.2500  24.8560
      2   0.2512  24.7223
            …       …      …
     40   0.9988   3.0079
     41   1.0000   3.0000

Note that Tip Pitch > 0 means ...
  i) Nose Down  or
 ii) Nose into the Wind

 ... this is different from Rotorcraft !
```

Input Modules

- Structure of Input File

&BLADE … &END	**Geometric Definitions**
&OPERATION … &END	**Design, Analysis, Prediction**
&SOLVER … &END	**Solver & Grid Selection**
&HVM … &END	**Helicoidal Vortex Method**
&BEMT … &END	**Blade Element Momentum Theory**

Input Modules

- Inputs - SOLVER

```
&SOLVER
  METHOD    = 2,
    JX      = 41,
   COSDISTR = 1,
    GNUPLOT = 0,
&END
```

```
  METHOD  =  1,
```
Blade Element Momentum Theory (BEMT)
```
          =  2,
```
Helicoidal Vortex Method (HVM)

```
    JX    =  # Radial Stations ('Odd' number!)
```

Input Modules

- Inputs - SOLVER

`COSDISTR = 0,`	**Uniform Spacing along Blade Span**	
`COSDISTR = 1,`	**Uniform Spacing along Blade Span** - Recommended for both BEMT & HVM	
`GNUPLOT = 0,`	**Default, i.e. <u>No</u> Output Files for gnuplot**	
`GNUPLOT = 1,`	**'Local' (Radial) Output** - Data File - Script File	
`GNUPLOT = 2,`	**'Local' (Radial) & 'Global' Output** - Data File - Script File	

Input Modules

- Structure of Input File

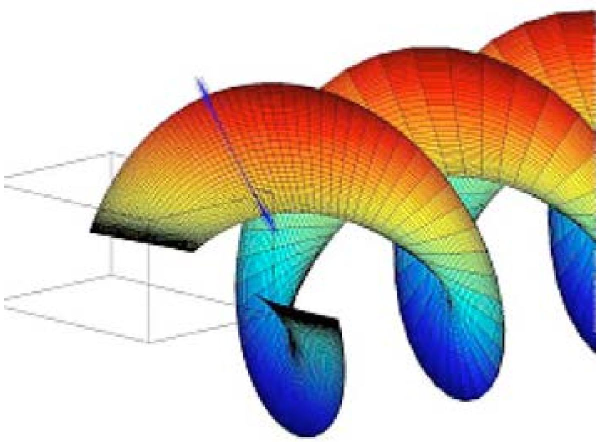
&BLADE … &END	Geometric Definitions
&OPERATION … &END	Design, Analysis, Prediction
&SOLVER … &END	Solver & Grid Selection
&HVM … &END	Helicoidal Vortex Method
&BEMT … &END	Blade Element Momentum Theory

Input Modules

- Inputs - HVM

```
&HVM
    WAKEEXP  = 1,
    DX0      = 1.E-04,
    XSTR     = 1.0,
    XTREFFTZ = 20.0,
    NSEC     = 30,
    IB       = 2,
    DIP      = 1,
    OMRELAX  = 0.2,
    AVISC    = 0.0,

    NACMOD   = 0,
    LN       = 0.050,
    HN       = 0.025,
    XN       = 0.000,
&END
```

DEFAULT Settings
No need to change !



Input Modules

- Inputs - HVM (Screen Output)

```
***** HVM *****

 +++++ Vortex Structure - HELIX +++++
         # Filaments jx-1 = 40
 End Mesh Stretching xstr = 1.
             Set xtrefftz = 20.
    Initial Mesh Step dx0 = 0.0001
   Number of Sectors nsec = 30

 +++++ Vortex Structure - BOUND +++++
         # Filaments jx-1 = 40
            # Segments ib = 2
                          = (jx-1)*(ib+1) = 120  Points

 +++++ Vortex Structure - Wake Expans./Contr. +++++
 Wake Expansion/Contraction    WAKEEXP = 0

 +++++ Influence Coefficients +++++
 Interval for Boundary Nodes  DIP = 1
```

Input Modules

- Inputs - HVM (Screen Output)

```
+++++ Solver Parameters +++++
Omega Relaxation Factor  = 0.2
Artificial Viscosity ... = 0.
 ... for separated flow

No Input specified for Nacelle Model !
```

OR (for NACMOD = 1)

```
+++ Nacelle Model +++

 Nacelle 1/2 Length (Rankine Body)    LN/R = 0.05
 Nacelle 1/2 Height (Rankine Body)    HN/R = 0.025
 Axial Location of Nacelle midpoint   XN/R = 0.

***** Nacelle Modeling (Rankine Body) *****
```

Input Modules

- Structure of Input File

&BLADE … &END	**Geometric Definitions**
&OPERATION … &END	**Design, Analysis, Prediction**
&SOLVER … &END	**Solver & Grid Selection**
&HVM … &END	**Helicoidal Vortex Method**
&BEMT … &END	**Blade Element Momentum Theory**

Input Modules

- Inputs - BEMT

DEFAULT Settings
No need to change !

```
&BEMT
    RLOSS     = 1,
    TLOSS     = 1,
    AXRELAX   = 0.125,
    ATRELAX   = 0.125,
&END
```

Root Loss Factor (AeroDyn)

Tip Loss Factor (AeroDyn)

Relaxation Factor for a

Relaxation Factor for a'

Output Files

- General Output
  - XTurb_Output.dat
  - XTurb_Output1.dat
  - XTurb_Output2.dat
  - XTurb_Output3.dat
- Method Specific Output
  - For BEMT & HVM : XTurb_Output_Method.dat
  - For HVM : adv.out, remain.out, bound.out, helix.out, blade_bound.out, blade_helix.out, coeff_coord.out, coeff_bound.out, coeff_helix.out, coeff_nacelle.out

Output Files

- General Output
  - XTurb_Output.dat

```
NREL-PhaseVI                                          ***** XTurb  -  OUTPUT *****
  Blade Number        BN =  2

  Solidity
  0.0519
                                  + Prescribed Wake Method [Chattot, Schmitz] +

  Number    TSR       PITCH [deg]      CT        CP         CPV       CB        CBV
       1    7.5850    3.0000           0.5472   -0.3287     0.0887   -0.3869   -0.0016
       2    5.4180    3.0000           0.5031   -0.3491     0.0314   -0.3475   -0.0011
        …        …         …                 …        …         …        …         …
```

Output Files

- General Output
  - XTurb_Output1.dat

```
++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

NREL-PhaseVI                              ***** XTurb  -  OUTPUT 1 *****
  Blade Number      BN =  2

  Solidity
  0.0519
                                 + Prescribed Wake Method [Chattot, Schmitz] +

  Number   TSR      PITCH [deg]      CT        CP        CPV       CB        CBV
       1   7.5850   3.0000           0.5472  -0.3287   0.0887  -0.3869  -0.0016

  "Thrust"   >   0      =>      Downwind Direction
  "Torque"   <   0      =>      Energy Extraction (Wind Turbine)   =>   Power = Torque * TSR
  "Bending"  <   0      =>      Flap Bending towards Downwind

  r/R  Chord/R Twist[deg] AOA[deg] PHI[deg] CL     CD     CL/CD    VSEC   VSECX  VSECY  VSECZ
------------------------------------------------------------------------------------------------
0.2500  0.1465  24.8560  -0.8872  23.9688  0.0417 0.0130 3.1985  2.1389  0.8689 -0.0140  1.9545
0.2512  0.1464  24.7223  -0.7218  24.0005  0.0612 0.0132 4.6444  2.1466  0.8731 -0.0139  1.9610
0.2546  0.1460  24.3221  -0.2279  24.0941  0.1191 0.0134 8.8652  2.1695  0.8857 -0.0138  1.9804
        …                  …                            …                            …
```

Output Files

- General Output
  - XTurb_Output2.dat

```
++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

NREL-PhaseVI                                  ***** XTurb  -  OUTPUT 2 *****
  Blade Number      BN =  2

  Solidity
  0.0519
                                 + Prescribed Wake Method [Chattot, Schmitz] +

  Number    TSR       PITCH [deg]      CT        CP        CPV       CB        CBV
       1    7.5850    3.0000           0.5472   -0.3287    0.0887   -0.3869   -0.0016

  "Thrust"   >   0      =>      Downwind Direction
  "Torque"   <   0      =>      Energy Extraction (Wind Turbine)   =>   Power = Torque * TSR
  "Bending"  <   0      =>      Flap Bending towards Downwind

r/R  Chord/R Twist[deg] AOA[deg] CL     CD     CDP     CM     CThrust  CTorque  CNormal  CTangen
-------------------------------------------------------------------------------------------------
0.2500 0.1465 24.8560  -0.8872   0.0417 0.0130 0.0067 -0.0408 0.0434  -0.0013   0.0415  -0.0137
0.2512 0.1464 24.7223  -0.7218   0.0612 0.0132 0.0067 -0.0413 0.0612  -0.0032   0.0610  -0.0139
         …                   …                             …                             …
```

Output Files

- General Output
  - XTurb_Output3.dat

```
+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

NREL-PhaseVI                                 ***** XTurb  -  OUTPUT 3 *****
  Blade Number      BN =  2

  Solidity
  0.0519
                                    + Prescribed Wake Method [Chattot, Schmitz] +

  Number    TSR      PITCH [deg]      CT        CP        CPV       CB        CBV
       1    7.5850   3.0000           0.5472  -0.3287    0.0887  -0.3869   -0.0016

  "Thrust"   >   0      =>      Downwind Direction
  "Torque"   <   0      =>      Energy Extraction (Wind Turbine)   =>   Power = Torque * TSR
  "Bending"  <   0      =>      Flap Bending towards Downwind

r/R  Chord/R Twist[deg] AOA[deg] PHI[deg] CL    CD     CL/CD  CThrust  CThrustV CTorque CTorqueV CBending CBendingV
-------------------------------------------------------------------------------------------------------------------
0.2500 0.1465 24.8560  -0.8872  23.9688 0.0417 0.0130 3.1985 0.0434   0.0053  -0.0013   0.0030  -0.0109  -0.0013
0.2512 0.1464 24.7223  -0.7218  24.0005 0.0612 0.0132 4.6444 0.0612   0.0054  -0.0032   0.0030  -0.0154  -0.0013
          …                    …                             …                                    …
```

Output Files

- Method Specific Output (HVM)
  - XTurb_Output_Method.dat

```
+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

NREL-PhaseVI                              ***** XTurb  -  OUTPUT 3 *****
  Blade Number      BN =  2

  Solidity
  0.0519
                                 + Prescribed Wake Method [Chattot, Schmitz] +

  Number   TSR      PITCH [deg]      CT        CP        CPV       CB        CBV
       1   7.5850   3.0000           0.5472  -0.3287    0.0887  -0.3869   -0.0016

  "Thrust"   >   0      =>      Downwind Direction
  "Torque"   <   0      =>      Energy Extraction (Wind Turbine)   =>   Power = Torque * TSR
  "Bending"  <   0      =>      Flap Bending towards Downwind

  "Axial   Induction Factor"   a       = -ui
  "Angular Induction Factor"   a_prime = +wi/(r/R*TSR)

r/R  Chord/R Twist[deg] AOA[deg] PHI[deg] CIRC    CL     CD     CL/CD    ui      vi      wi      a     a'
 --------------------------------------------------------------------------------------------------------
0.2500 0.1465 24.8560  -0.8872  23.9688  0.0000 0.0417 0.0130 3.1985 -0.1311 -0.0140  0.0582  0.1311  0.0307
0.2512 0.1464 24.7223  -0.7218  24.0005 -0.0096 0.0612 0.0132 4.6444 -0.1269 -0.0139  0.0559  0.1269  0.0294
     …                    …                                       …                                 …
```

Output Files

- Method Specific Output (BEMT)
  - XTurb_Output_Method.dat

```
+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

NREL-PhaseVI                              ***** XTurb  -  OUTPUT - METHOD *****
  Blade Number      BN =  2

  Solidity
  0.0519

                      +    BLADE ELEMENT MOMENTUM THEORY (BEMT)   +

  Number   TSR      PITCH [deg]      CT        CP        CPV       CB        CBV
       1   7.5850   3.0000           0.5420   -0.3229    0.0881   -0.3836   -0.0016

  "Thrust"   >   0      =>      Downwind Direction
  "Torque"   <   0      =>      Energy Extraction (Wind Turbine)   =>   Power = Torque * TSR
  "Bending"  <   0      =>      Flap Bending towards Downwind

  "Axial   Induction Factor"   a       = -ui
  "Angular Induction Factor"   a_prime = +wi/(r/R*TSR)

r/R   Chord/R Twist[deg] AOA[deg] PHI[deg] CL      CD      CL/CD    FR      FT      ui      wi      a        a'
 ------------------------------------------------------------------------------------------------------------
0.2500 0.1465  24.8560  -0.9001  23.9559  0.0402 0.0130  3.0846 0.0008 0.9990  -1.0000 -1.8962 1.0000  -1.0000
0.2512 0.1464  24.7223  -0.7680  23.9543  0.0557 0.0131  4.2431 0.0959 0.9996  -0.1418  0.0268 0.1418   0.0141
```

Output File - Convergence

- Convergence Output
  - XTurb_Convergence.dat

Lists any convergence issue that were encountered during the solution process

Is quite helpful in isolating convergence issues at specific radial stations

Output Files - *gnuplot*

- Output Files for *gnuplot*
  - XTurb_gnuplot_data.plt
  - XTurb_gnuplot_script.plt
  - XTurb_gnuplot_global_data.plt
  - XTurb_gnuplot_global_script.plt

`GNUPLOT = 1`

`GNUPLOT = 2`

- Run *gnuplot* (in terminal)

```
gnuplot    XTurb_gnuplot_script.plt
```

… creates a folder GNUPLOT/ with *.png plots.

```
gnuplot    XTurb_gnuplot_global_script.plt
```

… creates a folder GNUPLOT_GLOBAL/ with *.png plots.

“XTurb”

End - User’s Guide