Design of Wind Energy Systems

CARL VON OSSIETZKY universität OLDENBURG

ForWind Center for Wind Energy Research

CIP Tutorial 06a
Hints for the calculation of fatigue & extreme loads

Prof. Dr. M. Kühn

ForWind – Wind Energy Systems

Topics

- FAST overview
- Test case
- Load calculation
- Summary

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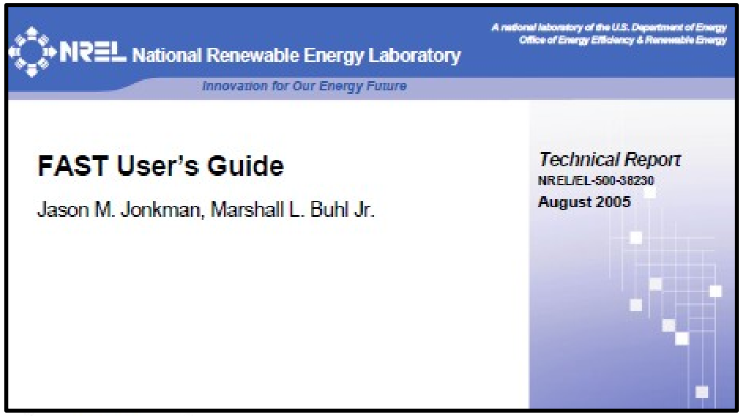
Load analysis – FAST

- Overview
- Test case
- Load calculation


National Renewable Energy Laboratory

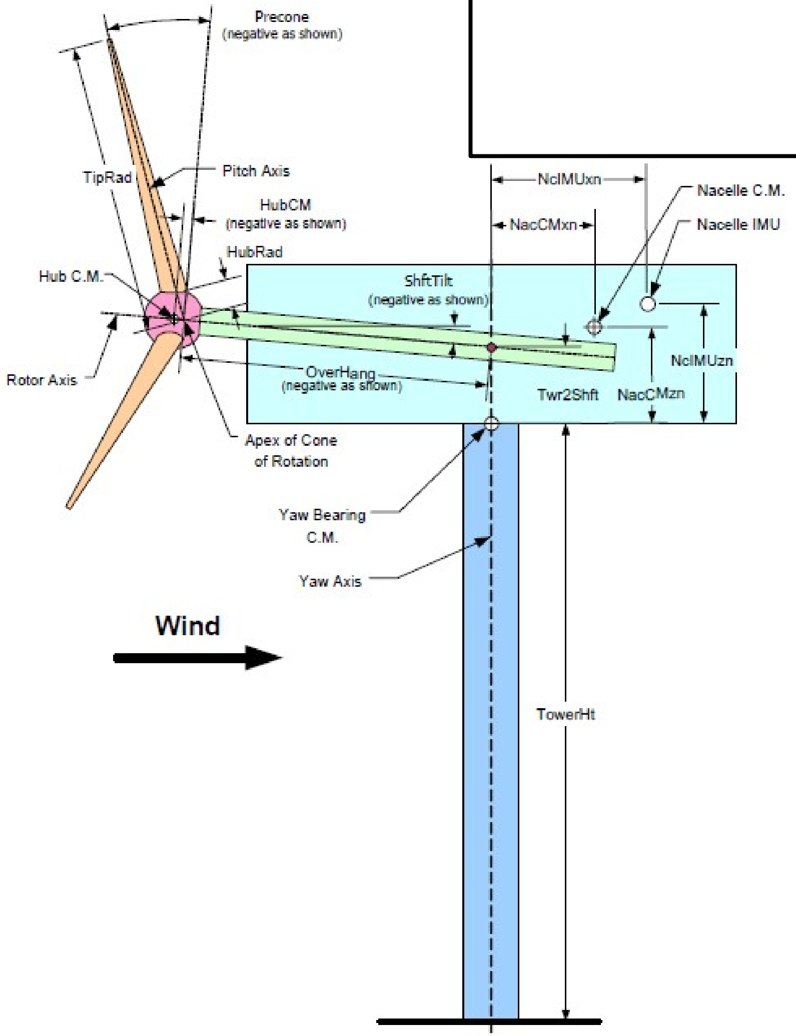
Innovation for Our Energy Future

A national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy

FAST User's Guide

Jason M. Jonkman, Marshall L. Buhl Jr.

Technical Report
NREL/EL-500-38230
August 2005



Overview – FAST

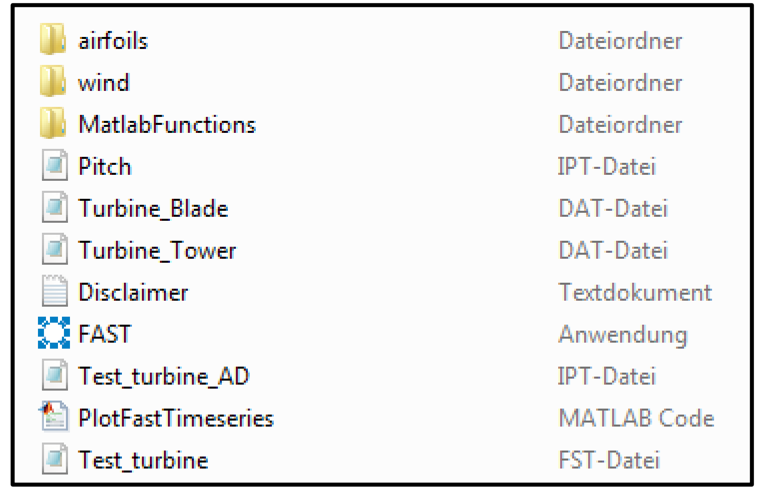
- **F**atigue, **A**erodynamics, **S**tructures & **T**urbulence code
- Wind turbine specific code
- Represent flexible elements using modal representation
- Few degrees of freedom (DOF)
- Aerodynamics with AeroDyn
- Open source

```
------- FAST INPUT FILE -------------------------------------------------------
Test file with data from WindPACT 1.5 MW turbine. LVT July 2014
File to be used @ DoWES 2014
---------------------- SIMULATION CONTROL ------------------------------------
False        Echo         - Echo input data to "echo.out" (flag)
   1         ADAMSPrep    - ADAMS preprocessor mode {1: Run FAST, 2: use FA
   1         AnalMode     - Analysis mode {1: Run a time-marching simulatio
   3         NumBl        - Number of blades (-)
 660.0       TMax         - Total run time (s)
   0.005     DT           - Integration time step (s)
---------------------- TURBINE CONTROL ---------------------------------------
   0         YCMode       - Yaw control mode {0: none, 1: user-defined from
9999.9       TYCOn        - Time to enable active yaw control (s) [unused w
   1         PCMode       - Pitch control mode {0: none, 1: user-defined fr
   5.0       TPCOn        - Time to enable active pitch control (s) [unused
   1         VSContrl     - Variable-speed control mode {0: none, 1: simple
1800.0       VS_RtGnSp    - Rated generator speed for simple variable-speed
8376.58      VS_RtTq      - Rated generator torque/constant generator torqu
   0.002585  VS_Rgn2K     - Generator torque constant in Region 2 for simpl
9999.9E-9    VS_SlPc      - Rated generator slip percentage in Region 2 1/2
   1         GenModel     - Generator model {1: simple, 2: Thevenin, 3: use
True         GenTiStr     - Method to start the generator {T: timed using T
True         GenTiStp     - Method to stop the generator {T: timed using Ti
9999.9       SpdGenOn     - Generator speed to turn on the generator for a 
   0.0       TimGenOn     - Time to turn on the generator for a startup (s)
9999.9       TimGenOf     - Time to turn off the generator (s) [used only w
   1         HSSBrMode    - HSS brake model {1: simple, 2: user-defined fro
9999.9       THSSBrDp     - Time to initiate deployment of the HSS brake (s
9999.9       TiDynBrk     - Time to initiate deployment of the dynamic gene
9999.9       TTpBrDp(1)   - Time to initiate deployment of tip brake 1 (s)
9999.9       TTpBrDp(2)   - Time to initiate deployment of tip brake 2 (s)
9999.9       TTpBrDp(3)   - Time to initiate deployment of tip brake 3 (s)
9999.9       TBDepISp(1)  - Deployment-initiation speed for the tip brake o
9999.9       TBDepISp(2)  - Deployment-initiation speed for the tip brake o
9999.9       TBDepISp(3)  - Deployment-initiation speed for the tip brake o
9999.9       TYawManS     - Time to start override yaw maneuver and end sta
9999.9       TYawManE     - Time at which override yaw maneuver reaches fin
   0.0       NacYawF      - Final yaw angle for yaw maneuvers (degrees)
9999.9       TPitManS(1)  - Time to start override pitch maneuver for blade
9999.9       TPitManS(2)  - Time to start override pitch maneuver for blade
9999.9       TPitManS(3)  - Time to start override pitch maneuver for blade
9999.9       TPitManE(1)  - Time at which override pitch maneuver for blade
9999.9       TPitManE(2)  - Time at which override pitch maneuver for blade
9999.9       TPitManE(3)  - Time at which override pitch maneuver for blade
   7.5       BlPitch(1)   - Blade 1 initial pitch (degrees)
   7.5       BlPitch(2)   - Blade 2 initial pitch (degrees)
   7.5       BlPitch(3)   - Blade 3 initial pitch (degrees) [unused for 2 b
```

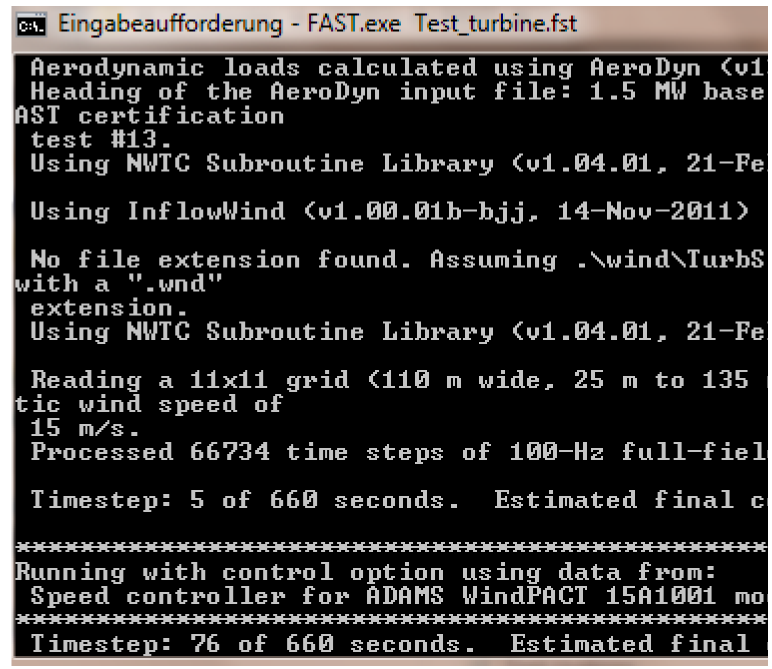
FAST main input file

Test case – FAST (1/4)

1. Unpack zip folder as C:\ FAST 2
2. Explore folder; it contains:
   - FAST.exe - executable
   - Test_turbine.fst – main input
   - Turbine_blade.dat & *_tower.dat, Pitch.ipt 3 – other input files
   - Test_turbine_AD.ipt – Aerodynamics & wind file references
   - Folders with airfoils & wind files
   - Matlab script & folder with functions
3. In DOS prompt go to directory (see 1)
   - Run test: **FAST Test_turbine.fst**



FAST folder



FAST executing in DOS prompt

Test case – FAST (2/4)

4. Review results in folder: 4
   - Test_turbine.opt – AeroDyn echo
   - Test_turbine.fsm – FAST summary
   - Test_turbine.out – FAST output file 5
5. Review the results in Test_turbine.out:
   - Results are written in columns, where the first one is time, followed by wind speed and all other outputs, as requested in input file Test_turbine.fst

Note: Use FAST_Users_guide.pdf to know how to change inputs

Test_turbine	FST-Datei
Test_turbine	OPT-Datei
Test_turbine	FSM-Datei
Test_turbine	OUT-Datei

FAST output files in folder

```
These predictions were generated by FAST (v7.01.00a-bjj, 16-Fe
The aerodynamic calculations were made by AeroDyn (v13.00.01a-

 Test file with data from WindPACT 1.5 MW turbine. LVT July 20

Time     WindVxi  WindVyi  WindVzi  RootMFlp2          RootMedg2
(s)       (m/s)    (m/s)    (m/s)   (kN·m)    (kN·m)   (kN)     (rpm)
  60.000           1.571E+01          5.766E-01          3.609E-01
  60.050           1.586E+01          1.097E-01          1.980E-01
  60.100           1.584E+01          1.285E-01          1.909E-01
  60.150           1.558E+01          5.162E-01          1.924E-01
  60.200           1.544E+01          6.082E-01         -2.012E-01
  60.250           1.513E+01          6.655E-01          1.477E-01
  60.300           1.482E+01          3.873E-01          3.654E-02
  60.350           1.543E+01          2.545E-01          4.254E-01
  60.400           1.550E+01          1.946E-02         -1.820E-01
  60.450           1.567E+01          1.844E-01          2.154E-01
  60.500           1.572E+01          3.871E-02         -4.945E-02
  60.550           1.614E+01          3.273E-01          3.548E-01
  60.600           1.641E+01          2.911E-01          7.701E-02
  60.650           1.627E+01         -4.224E-02          3.447E-01
  60.700           1.662E+01          6.203E-02          2.634E-01
  60.750           1.612E+01          5.939E-02          1.042E-02
  60.800           1.611E+01          4.565E-02          9.533E-01
  60.850           1.573E+01          3.007E-01          5.154E-01
  60.900           1.548E+01          1.501E-01          3.261E-01
  60.950           1.528E+01          5.610E-01          5.200E-01
  61.000           1.548E+01          8.214E-01          3.865E-01
  61.050           1.554E+01          7.147E-01          3.060E-01
  61.100           1.545E+01          1.105E+00          1.316E+00
  61.150           1.583E+01          2.144E+00          8.971E-01
  61.200           1.581E+01          2.681E+00          4.444E-01
  61.250           1.540E+01          2.230E+00          1.125E+00
  61.300           1.584E+01          2.244E+00          9.916E-01
  61.350           1.599E+01          1.859E+00          1.924E+00
  61.400           1.625E+01          1.966E+00          1.553E+00
  61.450           1.621E+01          1.948E+00          1.900E+00
  61.500           1.597E+01          2.033E+00          1.739E+00
```

FAST main output file

Test case – FAST (3/4)

6. Analyse results (timeseries) using Matlab script in folder:
   - PlotFastTimeseries.m
7. Timeseries statistics (a) & damage equivalent loads (b) can be read directly from Matlab workspace

6

airfoils	Dateiordner
wind	Dateiordner
MatlabFunctions	Dateiordner
Pitch	IPT-Datei
Turbine_Blade	DAT-Datei
Turbine_Tower	DAT-Datei
Disclaimer	Textdokument
FAST	Anwendung
Test_turbine_AD	IPT-Datei
PlotFastTimeseries	MATLAB Code
Test_turbine	FST-Datei

7a

Workspace

Name	Value
Damage_Eq_Loads	<1x1 struct>
FAST_output_file_...	'C:\FAST\Test_
FAST_results	<1x1 struct>

FAST_results ×

FAST_results <1x1 struct>

Field	Value	Min	Max	Mean	Std
header	<1x13 cell>				
Time	<12001x1 double>	60	660	360	173.2267
WindVxi	<12001x1 double>	9.0490	21.8600	14.9613	1.9743
WindVyi	<12001x1 double>	-5.1720	4.4750	-0.0479	1.3500
WindVzi	<12001x1 double>	-3.5220	2.8440	-0.0060	0.8048
RootMFlp2	<12001x1 double>	31.5700	1482	802.9375	215.2980
RootMedg2	<12001x1 double>	-497.3000	572.4000	26.5339	316.1732
RotThrust	<12001x1 double>	97.3200	212.2000	151.6548	18.5404
RotSpeed	<12001x1 double>	19.4800	21.4500	20.4751	0.3443
TwrBsMyt	<12001x1 double>	4814	15330	9.9923e+03	1.6872e+03
TwrBsMxt	<12001x1 double>	-1110	2728	801.4473	543.3289
GenPwr	<12001x1 double>	1294	1572	1.4818e+03	49.8799
GenTq	<12001x1 double>	7.5900	8.3770	8.2679	0.1528
BldPitch2	<12001x1 double>	7.4160	20.5700	14.1270	2.7531

7b

Workspace

Name	Value
Damage_Eq_Loads	<1x1 struct>
FAST_output_file_...	'C:\FAST\Test_
FAST_results	<1x1 struct>

Damage_Eq_Loads <1x1 struct>

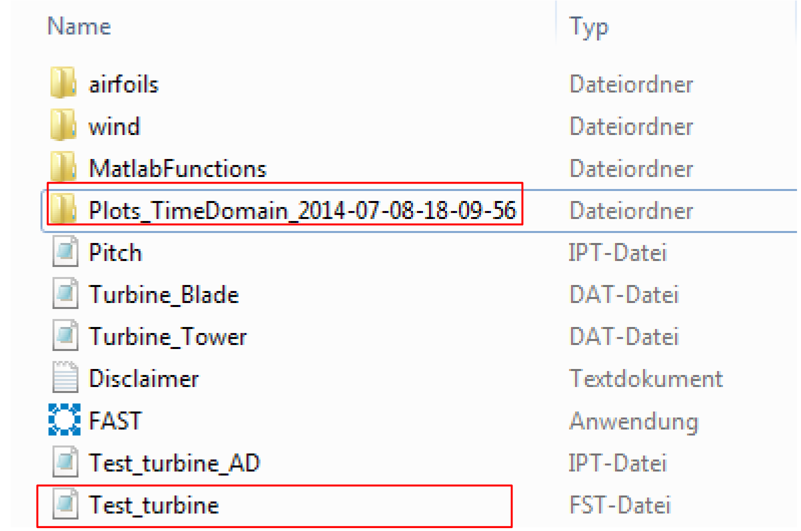
Field	Value
RootMFlp_Req	606.9395
RootMFlp_m	10
RootMedg_Req	790.7247
RootMedg_m	10
TwrBsMyt_Req	2.0539e+03
TwrBsMyt_m	4
TwrBsMxt_Req	1.1630e+03
TwrBsMxt_m	4

Test case – FAST (4/4)

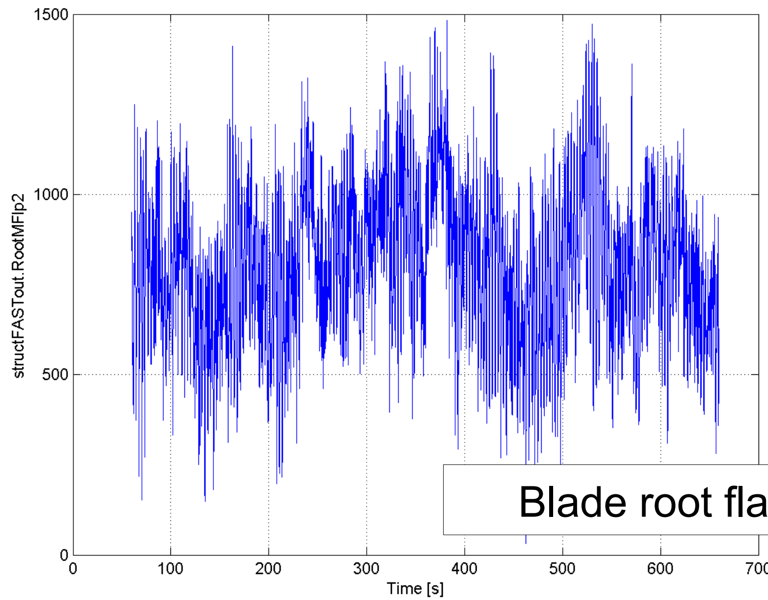
8. Timeseries are placed in folder "Plot_TimeDomain + date & time"
9. Description of outputs in Turbine_test.fst
10. Power spectral density created with Matlab script PlotFastTimeseries.m

8

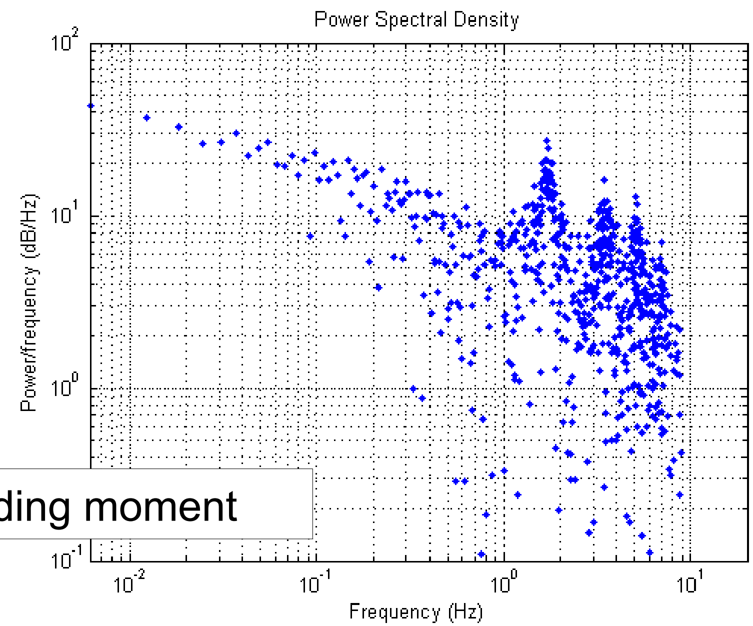
9



8



10



Blade root flapwise bending moment

Load calculation – FAST (1/x)

1. Comment 2-lines header for traceability: “color”, user & date
2. Select algorithms for calculation
3. Update “Turbine Data” section (if some are unknown, keep default)

1

```
-----  WT_Perf Input File  -----------------------------------
"Test" Wind turbine - file example for DOWES CIP Tutorial 03
created by LVT 20th May 2014
-----   Input Configuration  --------------------------------
```

2

```
-----   Algorithm Configuration  --------------------------------------------
True                   TipLoss:                  Use the Prandtl tip-loss model?
True                   HubLoss:                  Use the Prandtl hub-loss model?
True                   Swirl:                    Include Swirl effects?
True                   SkewWake:                 Apply skewed-wake correction?
True                   IndType:                  Use BEM induction algorithm?
True                   AIDrag:                   Use the drag term in the axial i
False                  TIDrag:                   Use the drag term in the tangent
False                  TISingularity:            Use the singularity avoidance met
False                  DAWT:                     Run Diffuser Augmented Water Turb
False                  Cavitation:               Run cavitation check? if cavitat
```

3

```
-----   Turbine Data  -------------------------------------------------------
 3                     NumBlade:                 Number of blades.
35.95                  RotorRad:                 Rotor radius [length].
 1.2                   HubRad:                   Hub radius [length or div by rad
-3.0                   PreCone:                  Precone angle, positive downwind
 5.0                   Tilt:                     Shaft tilt [deg].
 0.0                   Yaw:                      Yaw error [deg].
70.0                   HubHt:                    Hub height [length or div by rad
 8                     NumSeg:                   Number of blade segments (entire
   RElm    Twist     Chord   AFfile  PrntElem
3.421875         29.36987577     5.070530343     1       FALSE
7.765625         14.20925825     4.459489198     1       FALSE
12.109375        6.823436492     3.384116952     1       FALSE
16.453125        2.753876508     2.650669029     1       FALSE
20.796875        0.230641975     2.160752278     2       FALSE
25.140625        -1.473157945    1.815959346     2       FALSE
29.484375        -2.69646261     1.563239845     2       FALSE
33.828125        -3.615679163    1.370923606     2       FALSE
```

Load calculation – FAST (2/x)

1. Comment 2-lines header for traceability: “color”, user & date
2. Select algorithms for calculation
3. Update “Turbine Data” section (if some are unknown, keep default)
4. Enter blade geometry (from CIP-01 file “*_start_parameters.xlsx”)
   - Relm – center of section
   - AFfile – aerodynamic profile
   - PrntElem – keep as false

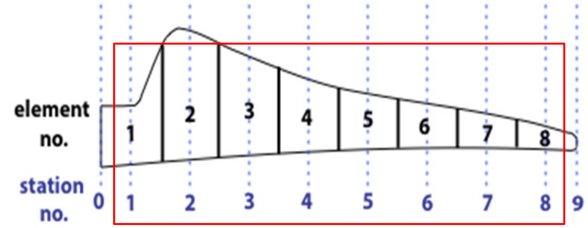
Note: correct RotorRad, for precone & tilt (follow error message)

```
-----  WT_Perf Input File  -----------------------------------
"Test" Wind turbine - file example for DOWES CIP Tutorial 03
created by LVT 20th May 2014
-----  Input Configuration  ----------------------------------
```

```
-----  Algorithm Configuration  ------------------------------------------------
True             TipLoss:          Use the Prandtl tip-loss model?
True             HubLoss:          Use the Prandtl hub-loss model?
True             Swirl:            Include Swirl effects?
True             SkewWake:         Apply skewed-wake correction?
True             IndType:          Use BEM induction algorithm?
True             AIDrag:           Use the drag term in the axial i
False            TIDrag:           Use the drag term in the tangent
False            TISingularity:    Use the singularity avoidance met
False            DAWT:             Run Diffuser Augmented Water Turb
False            Cavitation:       Run cavitation check? if cavitat
```

4

```
-----  Turbine Data  -----------------------------------------------------------
 3               NumBlade:         Number of blades.
35.95            RotorRad:         Rotor radius [length].
 1.2             HubRad:           Hub radius [length or div by rad
-3.0             PreCone:          Precone angle, positive downwind
 5.0             Tilt:             Shaft tilt [deg].
 0.0             Yaw:              Yaw error [deg].
70.0             HubHt:            Hub height [length or div by rad
 8               NumSeg:           Number of blade segments (entire
   RElm    Twist     Chord   AFfile   PrntElem
3.421875        29.36987577     5.070530343     1       FALSE
7.765625        14.20925825     4.459489198     1       FALSE
12.109375       6.823436492     3.384116952     1       FALSE
16.453125       2.753876508     2.650669029     1       FALSE
20.796875       0.230641975     2.160752278     2       FALSE
25.140625       -1.473157945    1.815959346     2       FALSE
29.484375       -2.69646261     1.563239845     2       FALSE
33.828125       -3.615679163    1.370923606     2       FALSE
```



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Load calculation – FAST (3/x)

5. Update the aerodynamic data
   - NumAF – 2 airfoils
   - Path to airfoils
6. Define outputs requested to investigate turbine performance
7. Define ranges for variation of:
   - Pit(St/End/Del) – pitch values
   - Omg() – rotor speed
   - Spd() – speed (in example given as tip speed ratio)

Note: Study results in spreadsheets

5

```
-----  Aerodynamic Data  ------------------------------------------------------
1.225                                          Rho:                Air density [mass/v
1.4639e-5                                      KinVisc:            Kinematic air visco
0.0                                            ShearExp:           Wind shear exponent
True                                           UseCm:              Are Cm data include
False                                          UseCpmin:           Are Cp,min data inc
2                                              NumAF:              Number of airfoil f
"C:\WT_Perf\Airfoils\NACA_63_218.dat"
"C:\WT_Perf\Airfoils\NACA_63_215.dat"
```

```
-----  Output Configuration  --------------------------------------------------
False                   UnfPower:                 Write parametric power to a
True                    TabDel:                   Make output tab-delimited (
1                       ConvFlag:                 For non-converging cases, C
True                    Beep:                     Beep if errors occur.
True                    KFact:                    Output dimensional paramete
False                   WriteBED:                 Write out blade element dat
True                    InputTSR:                 Input speeds as TSRs?
True                    OutMaxCp:                 Output conditions for the m
"mps"                   SpdUnits:                 Wind-speed units (mps, fps,
-----  Combined-Case Analysis  ------------------------------------------------
0                       NumCases:                 Number of cases to run.  En
WS or TSR    RotSpd     Pitch                     Remove following block of l
-----  Parametric Analysis (Ignored if NumCases > 0 )  -----------------------
3                       ParRow:                   Row parameter    (1-rpm, 2-
1                       ParCol:                   Column parameter (1-rpm, 2-
2                       ParTab:                   Table parameter  (1-rpm, 2-
False                   OutPwr:                   Request output of rotor pow
True                    OutCp:                    Request output of Cp?
True              6     OutTrq:                   Request output of shaft tor
False                   OutFlp:                   Request output of flap benc
True                    OutThr:                   Request output of rotor thr
-5, 5, 1                PitSt, PitEnd, PitDel:    First, last, delta blade pi
22, 24, 0.25            OmgSt, OmgEnd, OmgDel:    First, last, delta rotor sp
1, 10, 0.1        7     SpdSt, SpdEnd, SpdDel:    First, last, delta speeds.
```

Summary / Conclusion

- We completed our first calculation with FAST
- We reviewed how to modify input files to evaluate the turbine