Design of Wind Energy Systems

CIP Tutorial 03
Hints for the calculation of performance curves

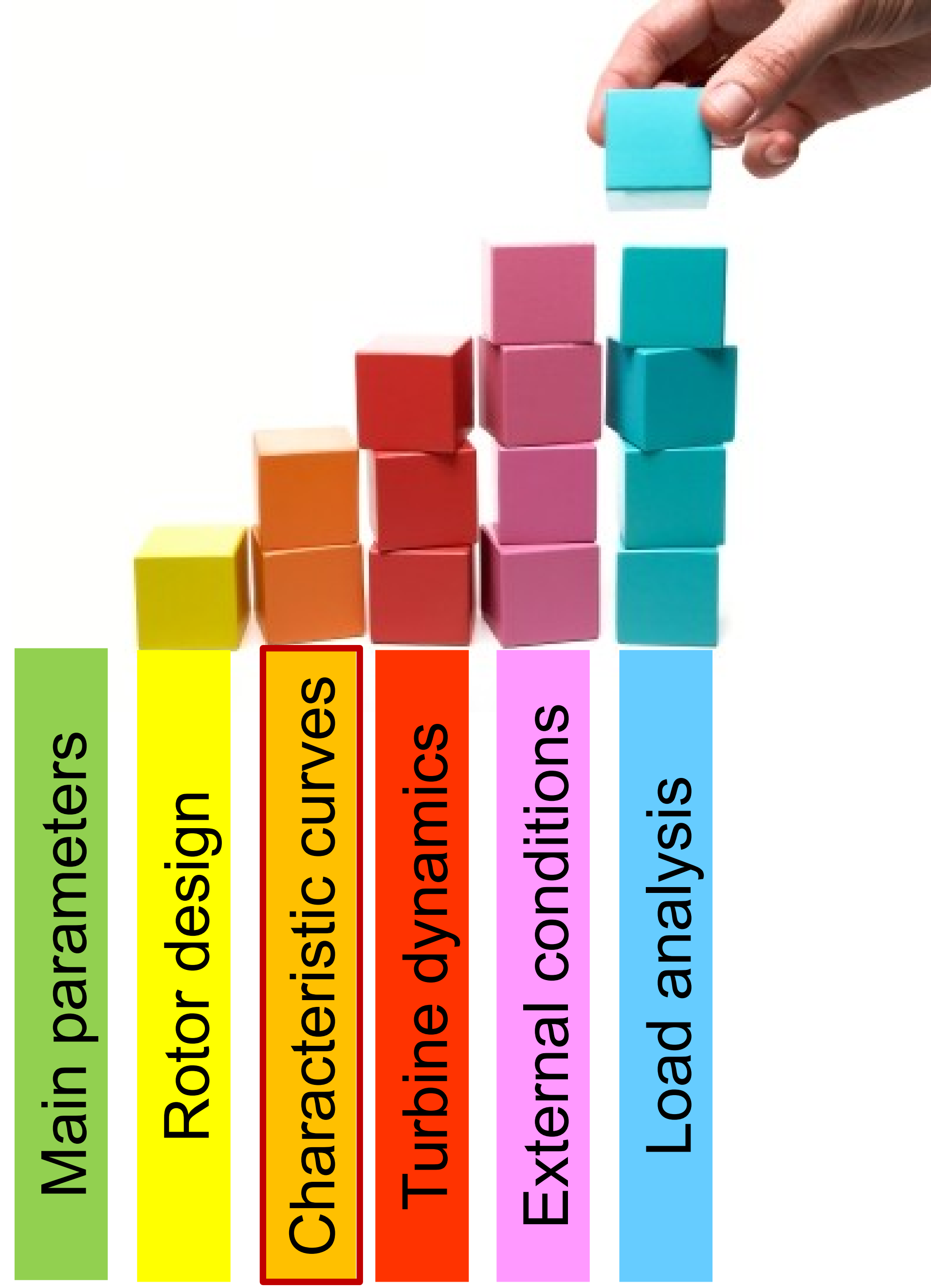
Prof. Dr. M. Kühn

ForWind – Wind Energy Systems

Topics

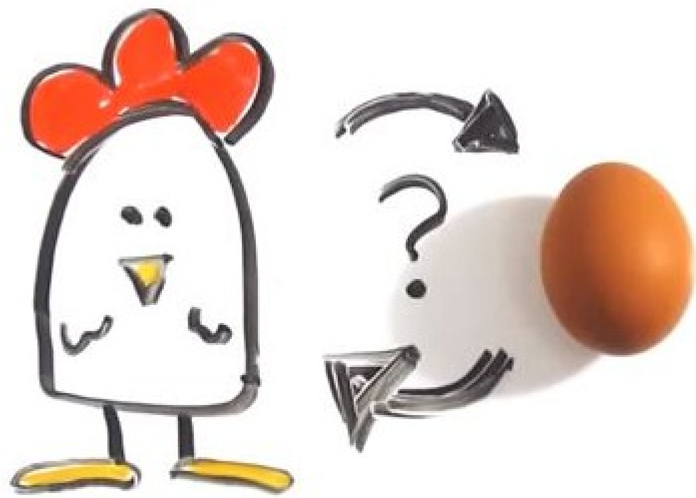
- Previous design steps
- Dimensional & non-dimensional performance curves
- Performance curves – WT_Perf
- Summary

CIP Tutorials



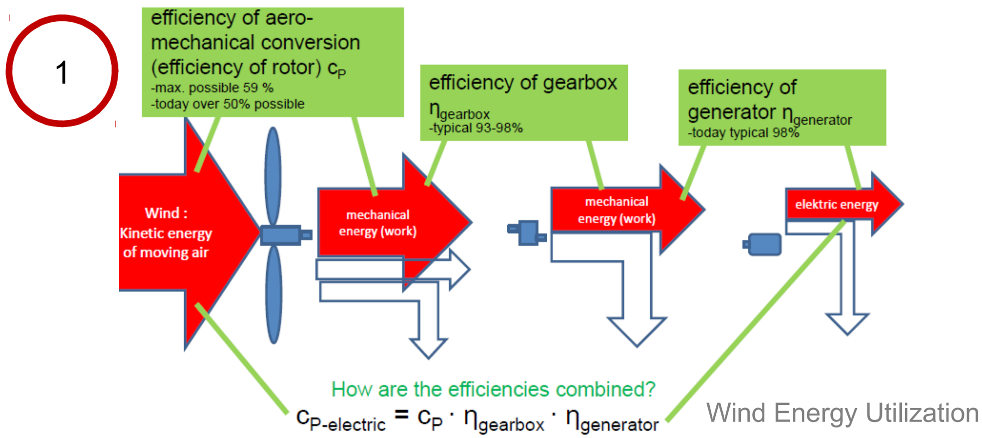
Previous design steps

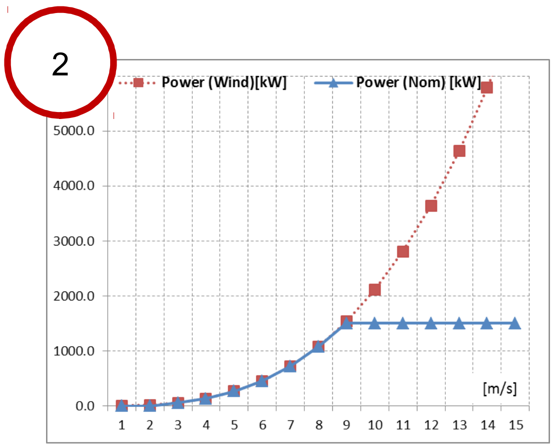
- Where did we start?

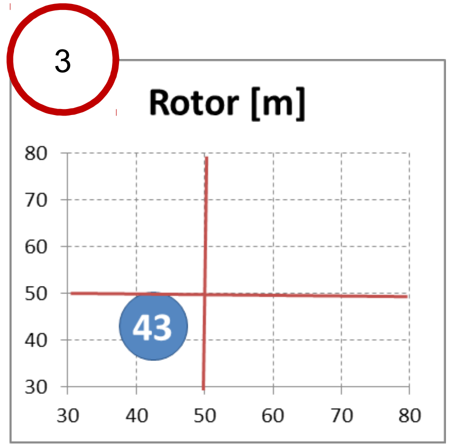


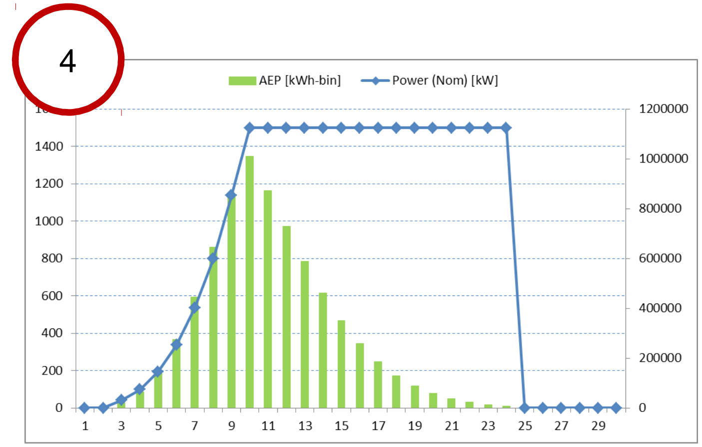
Previous design steps (1/3)

1. From wind to electrical power
2. Selection of rated wind speed & rated power
3. Selection of rotor diameter
4. Study the impact of rated wind speed & rotor diameter on AEP





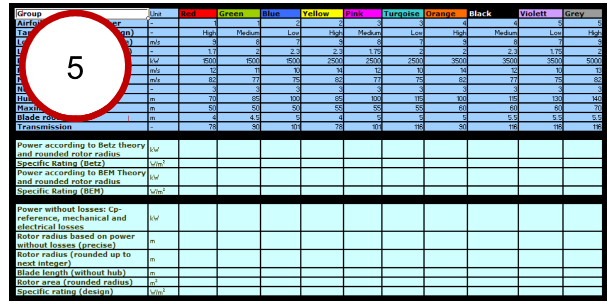




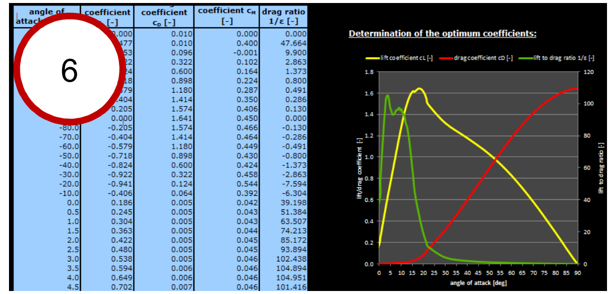
CARL VON OSSIETZKY universität OLDENBURG

Previous design steps (2/3)

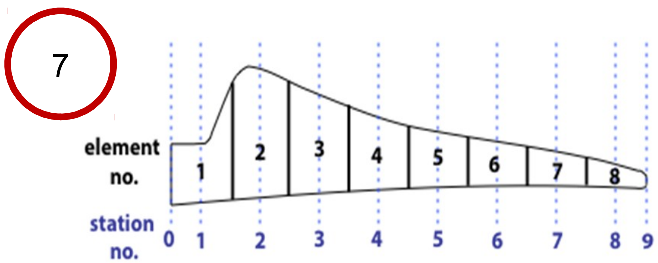
5. Estimation of other parameters: rating, design tip speed ratio, rotor speed, etc.
6. Selection of airfoil & optimum design point
7. Definition of blade geometry: twist angle & chord length

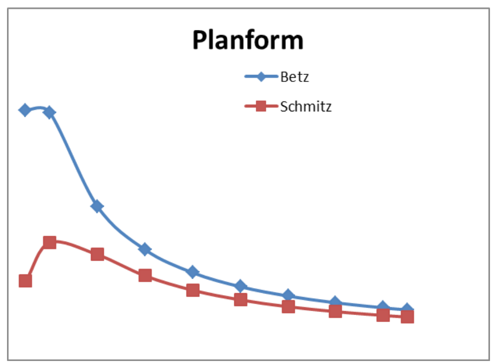


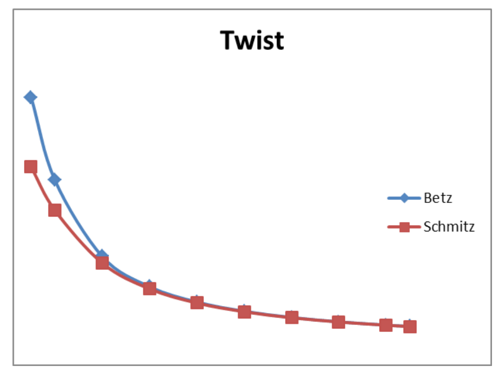
Group	Unit	Red	Green	Blue	Yellow	Pink	Turqoise	Orange	Black	Violett	Grey
Airfoi[illegible]er	-	1	1	2	2	3	3	4	4	5	5
Ta[illegible]gn)	-	High	Medium	Low	High	Medium	Low	High	Medium	Low	High
Lo[illegible]e)	m/s	9	8	7	9	8	7	9	8	7	9
L[illegible])	-	1.7	2	2.3	2.3	1.75	2	2	2.3	1.75	2
[illegible]	kW	1500	1500	1500	2500	2500	2500	3500	3500	3500	5000
[illegible]	m/s	12	11	10	14	12	10	14	12	10	13
M[illegible]	m/s	82	77	75	82	77	75	82	77	75	82
N[illegible]	-	3	3	3	3	3	3	3	3	3	3
Hu[illegible]	m	70	85	100	85	100	115	100	115	130	140
Maxi[illegible]	m	50	50	50	55	55	55	60	60	60	70
Blade ro[illegible]	m	4	4.5	5	4	5	5	5	5.5	5.5	5.5
Transmission	-	78	90	101	78	101	116	90	116	116	116
Power according to Betz theory and rounded rotor radius	kW										
Specific Rating (Betz)	W/m²										
Power according to BEM Theory and rounded rotor radius	kW										
Specific Rating (BEM)	W/m²										
Power without losses: Cp-reference, mechanical and electrical losses	kW										
Rotor radius based on power without losses (precise)	m										
Rotor radius (rounded up to next integer)	m										
Blade length (without hub)	m										
Rotor area (rounded radius)	m²										
Specific rating (design)	W/m²										



angle of attac[illegible]	coefficient [illegible] [-]	coefficient c_D [-]	coefficient c_M [-]	drag ratio $1/\varepsilon$ [-]
[illegible]	[illegible]	0.010	0.000	0.000
[illegible]	[illegible]	0.010	0.400	47.664
[illegible]	[illegible]	0.096	-0.001	9.900
[illegible]	[illegible]	0.322	0.102	2.863
[illegible]	[illegible]	0.600	0.164	1.373
[illegible]	[illegible]	0.898	0.224	0.800
[illegible]	[illegible]	1.180	0.287	0.491
[illegible]	[illegible]	1.414	0.350	0.286
[illegible]	0.205	1.574	0.406	0.130
[illegible]	0.000	1.641	0.450	0.000
-80.0	-0.205	1.574	0.466	-0.130
-70.0	-0.404	1.414	0.464	-0.286
-60.0	-0.579	1.180	0.449	-0.491
-50.0	-0.718	0.898	0.430	-0.800
-40.0	-0.824	0.600	0.424	-1.373
-30.0	-0.922	0.322	0.458	-2.863
-20.0	-0.941	0.124	0.544	-7.594
-10.0	-0.406	0.064	0.392	-6.304
0.0	0.186	0.005	0.042	39.198
0.5	0.245	0.005	0.043	51.384
1.0	0.304	0.005	0.043	63.507
1.5	0.363	0.005	0.044	74.213
2.0	0.422	0.005	0.045	85.172
2.5	0.480	0.005	0.045	93.894
3.0	0.538	0.005	0.046	102.438
3.5	0.594	0.006	0.046	104.894
4.0	0.649	0.006	0.046	104.951
4.5	0.702	0.007	0.046	101.416

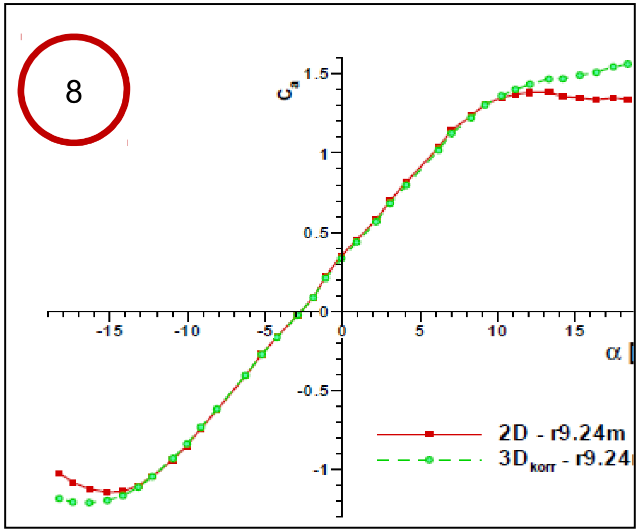




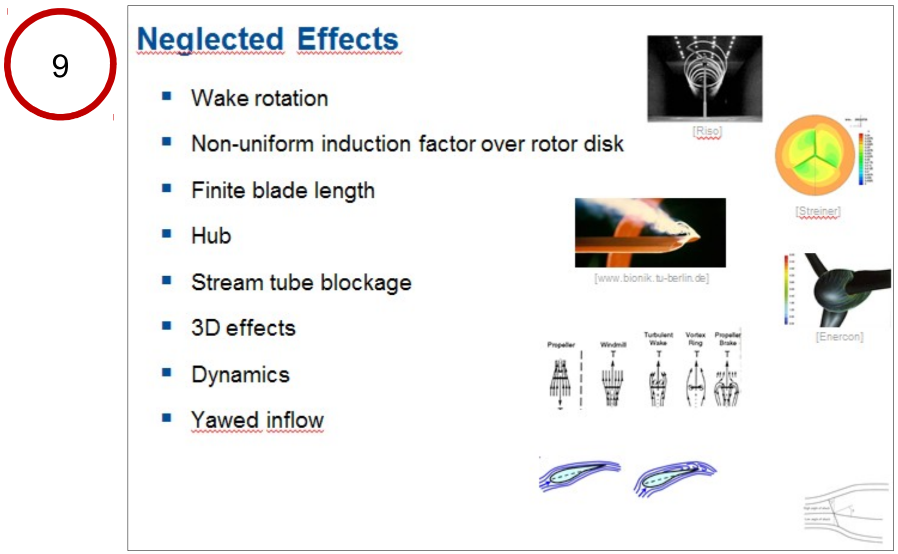


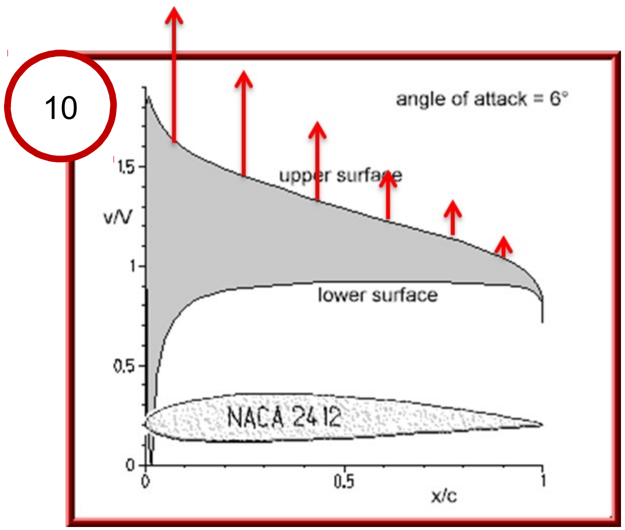
Previous design steps (3/3)

8. Correction of airfoil curves from 2-D to 3-D effects
9. Described BEM theory corrections & estimated Prandtl tip & root loss
10. Estimated pitch moment



[Fig. Streiner]





[mh-aerotools]

Dimensional & non-dimensional curves

Non-dimensional curves

Equations from "actuator disk" theory:

- Power coefficient

$$c_P = \frac{\text{rotor power}}{\text{wind power}} = \frac{P}{\frac{\rho}{2} \cdot F \cdot V_1^3} = 4a \cdot (1-a)^2$$

- Thrust coefficient

$$c_s = \frac{\text{thrust}}{\text{impact pressure}} = \frac{S}{\frac{\rho}{2} \cdot F \cdot V_1^2} = 4a \cdot (1-a)$$

Remind @ Betz optimum: a = 1/3

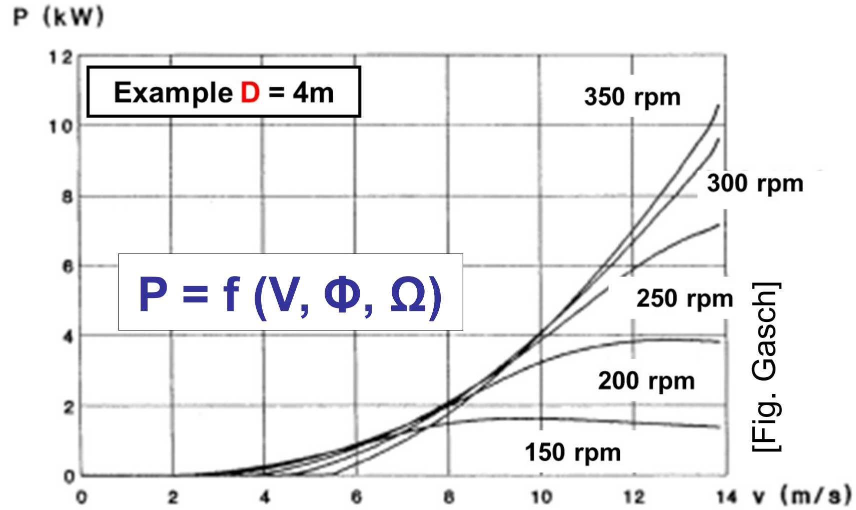
Remind @ Betz optimum: c_p = 16/27

Remind @ Betz optimum: c_S = 8/9

Dimensional & non-dimensional curves

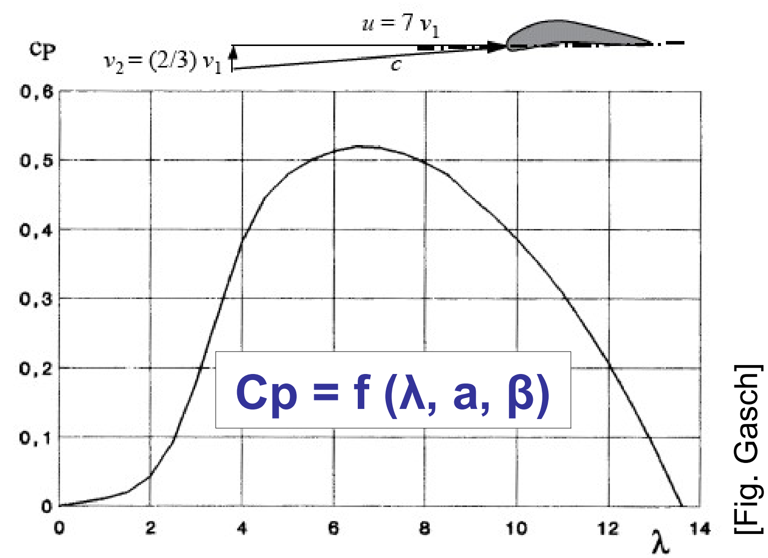
Dimensional performance curves are:

i. used for simple control & regulation
ii. only valid for specific turbine



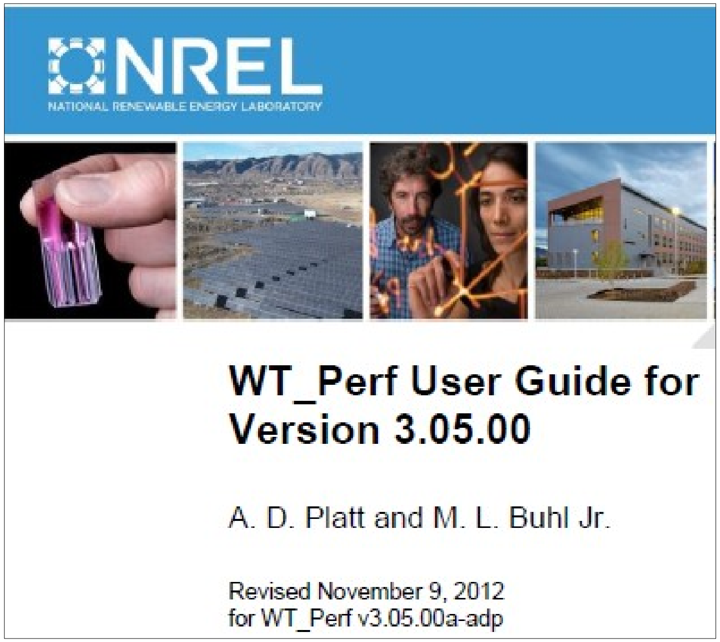
Non-dimensional performance curves are:

iii. independent from the specific turbine
iv. can be scaled for new turbines



Performance curves – WT_Perf

- Overview
- Test case
- Wind turbine performance


NREL
NATIONAL RENEWABLE ENERGY LABORATORY

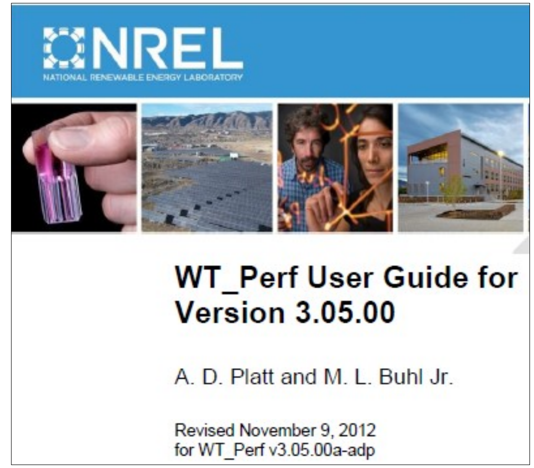
WT_Perf User Guide for Version 3.05.00

A. D. Platt and M. L. Buhl Jr.

Revised November 9, 2012
for WT_Perf v3.05.00a-adp

Overview – WT_Perf

- Based on BEM theory
- Includes algorithm to account for tangential induction factor
- It can include drag in the calculation of induction factors
- It has algorithms for tip & loss correction
- It corrects for tilt & yaw rotor
- DOS executable using ASCII input file & airfoil files



WT_Perf User guide

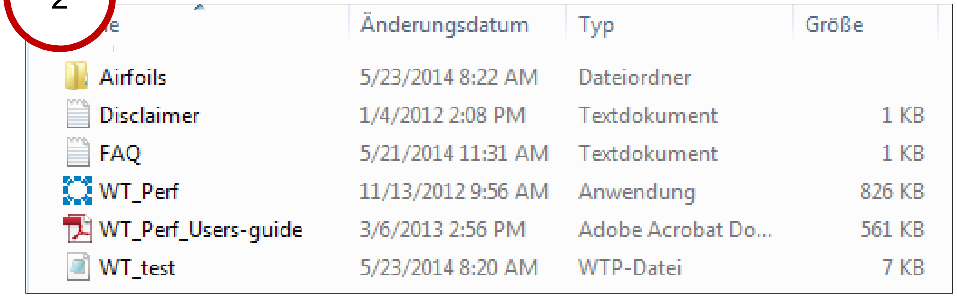
```
-----  WT_Perf Input File  -----------------------------------------------------------
"Test" Wind turbine - file example for DOWES CIP Tutorial 03
created by LVT 20th May 2014
-----  Input Configuration  ----------------------------------------------------------
True                     Echo:                     Echo input parameters to "
True                     DimenInp:                 Turbine parameters are dim
True                     Metric:                   Turbine parameters are Met
-----  Model Configuration  ----------------------------------------------------------
4                        NumSect:                  Number of circumferential
13                       MaxIter:                  Max number of iterations f
25                       NSplit:                   Max number of splits for b
1.0e-5                   ATol:                     Error tolerance for induct
1.0e-5                   SWTol:                    Error tolerance for skewed
-----  Algorithm Configuration  ------------------------------------------------------
False                    TipLoss:                  Use the Prandtl tip-loss m
False                    HubLoss:                  Use the Prandtl hub-loss m
False                    Swirl:                    Include Swirl effects?
False                    SkewWake:                 Apply skewed-wake correcti
True                     IndType:                  Use BEM induction algorith
False                    AIDrag:                   Use the drag term in the a
False                    TIDrag:                   Use the drag term in the t
False                    TISingularity:            Use the singularity avoida
False                    DAWT:                     Run Diffuser Augmented Wat
False                    Cavitation:               Run cavitation check? if c
-----  Cavitation Model  -------------------------------------------------------------
101325                   PressAtm:                 Air Atmospheric Pressure,
2500                     PressVapor:               Vapor Pressure of Water, P
1.0                      CavSF:                    Cavitation safety factor
0.0                      WatDepth:                 Depth from water free surf
-----  Turbine Data  -----------------------------------------------------------------
 3                       NumBlade:                 Number of blades.
35.95                    RotorRad:                 Rotor radius [length].
 1.2                     HubRad:                   Hub radius [length or div
-3.0                     PreCone:                  Precone angle, positive do
 5.0                     Tilt:                     Shaft tilt [deg].
 0.0                     Yaw:                      Yaw error [deg].
```

WT_Perf Input file

Test case – WT_Perf (1/2)

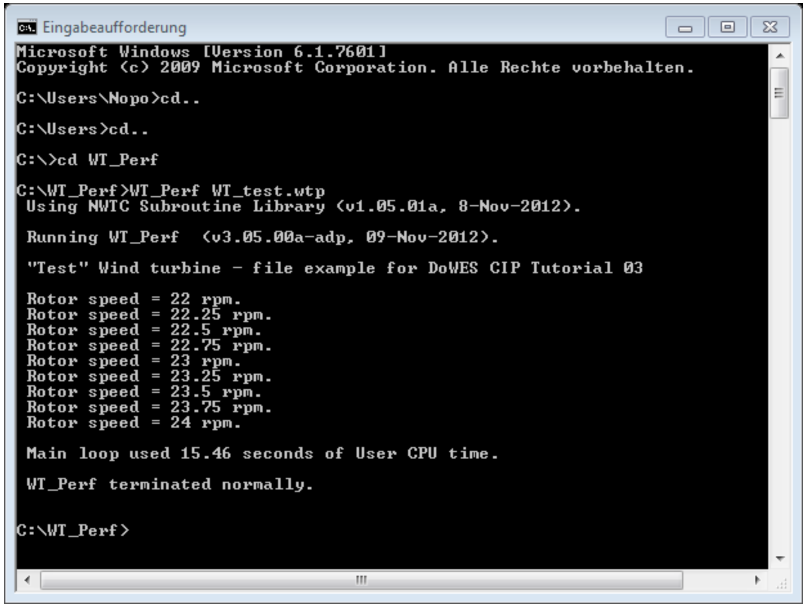
1. Unpack zip folder as C:\ WT_Perf
   - ➢ If other location is used, correct paths in input files!
2. Explore folder; it contains:
   - WT_Perf.exe
   - WT_Perf_Users-guide.pdf
   - WT_test.wtp – test input file
   - Folder with set of airfoils
   - Disclaimer & FAQ text files
3. In DOS prompt go to directory (see 1)
   - Run test: **WT_Perf WT_test.wtp**

2



WT_Perf folder

3



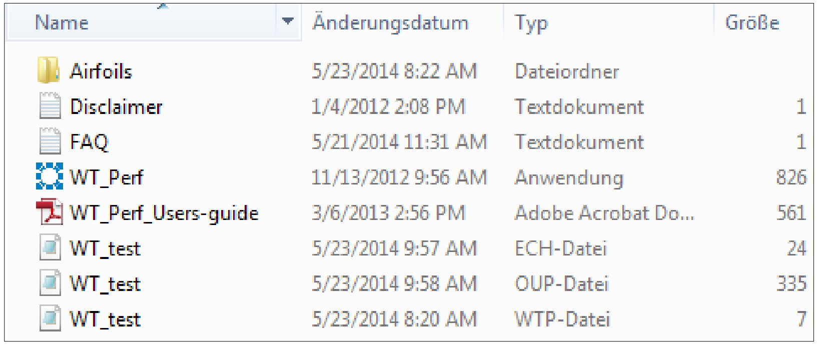
WT_Perf commands in DOS

Test case – WT_Perf (2/2)

4. Review results in folder:
   - WT_test.ech – echo input file
   - WT_test.oup – output file
5. Review the results:
   - It contains requested outputs (as described “Output Configuration”) from WT_test.wtp

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

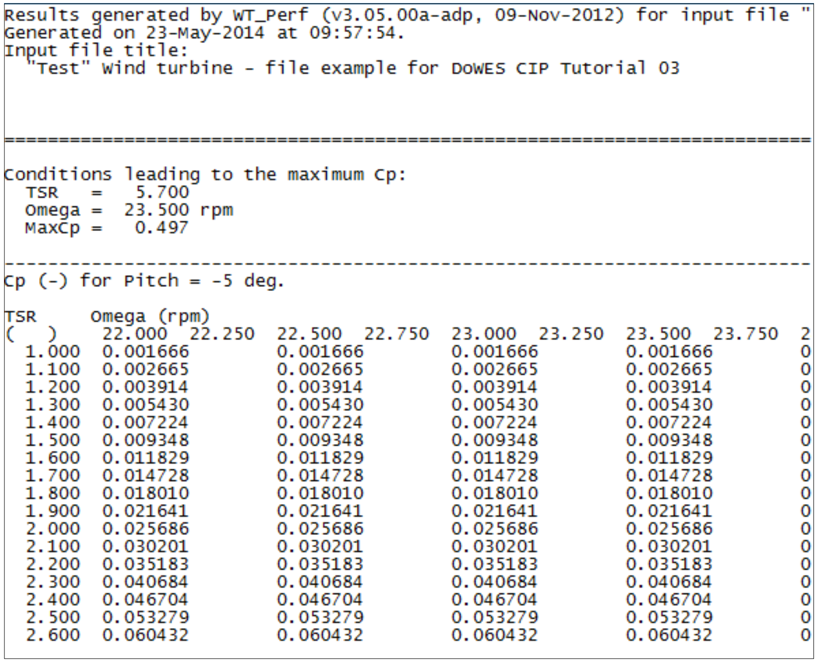
4



Name	Änderungsdatum	Typ	Größe
Airfoils	5/23/2014 8:22 AM	Dateiordner	
Disclaimer	1/4/2012 2:08 PM	Textdokument	1
FAQ	5/21/2014 11:31 AM	Textdokument	1
WT_Perf	11/13/2012 9:56 AM	Anwendung	826
WT_Perf_Users-guide	3/6/2013 2:56 PM	Adobe Acrobat Do...	561
WT_test	5/23/2014 9:57 AM	ECH-Datei	24
WT_test	5/23/2014 9:58 AM	OUP-Datei	335
WT_test	5/23/2014 8:20 AM	WTP-Datei	7

WT_Perf folder with results

5



```
Results generated by WT_Perf (v3.05.00a-adp, 09-Nov-2012) for input file "
Generated on 23-May-2014 at 09:57:54.
Input file title:
  "Test" wind turbine - file example for DOWES CIP Tutorial 03



==========================================================================

Conditions leading to the maximum Cp:
  TSR   =   5.700
  Omega =  23.500 rpm
  MaxCp =   0.497

--------------------------------------------------------------------------
Cp (-) for Pitch = -5 deg.

TSR      Omega (rpm)
(   )     22.000   22.250   22.500   22.750   23.000   23.250   23.500   23.750   2
  1.000   0.001666          0.001666          0.001666          0.001666          0
  1.100   0.002665          0.002665          0.002665          0.002665          0
  1.200   0.003914          0.003914          0.003914          0.003914          0
  1.300   0.005430          0.005430          0.005430          0.005430          0
  1.400   0.007224          0.007224          0.007224          0.007224          0
  1.500   0.009348          0.009348          0.009348          0.009348          0
  1.600   0.011829          0.011829          0.011829          0.011829          0
  1.700   0.014728          0.014728          0.014728          0.014728          0
  1.800   0.018010          0.018010          0.018010          0.018010          0
  1.900   0.021641          0.021641          0.021641          0.021641          0
  2.000   0.025686          0.025686          0.025686          0.025686          0
  2.100   0.030201          0.030201          0.030201          0.030201          0
  2.200   0.035183          0.035183          0.035183          0.035183          0
  2.300   0.040684          0.040684          0.040684          0.040684          0
  2.400   0.046704          0.046704          0.046704          0.046704          0
  2.500   0.053279          0.053279          0.053279          0.053279          0
  2.600   0.060432          0.060432          0.060432          0.060432          0
```

WT_Perf commands in DOS

Wind turbine performance – WT_Perf (1/3)

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 me
False                  DAWT:                   Run Diffuser Augmented Water Tur
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
```

Wind turbine performance – WT_Perf (2/3)

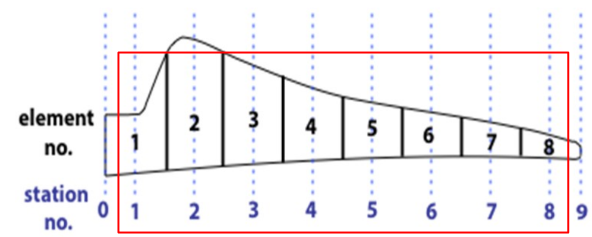
1. Comment 2-lines header for traceability: “color”, user & date
2. Select algorithms for calculation
3. Update “Turbine Data” section (if some are unknown, keep default)
4. Enter blade geometry (from CIP-01 file “*_start_parameters.xlsx”)
   - Relm – center of section
   - AFfile – aerodynamic profile
   - 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 me
False                DAWT:                  Run Diffuser Augmented Water Turb
False                Cavitation:            Run cavitation check? if cavitat

-----  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
```



CARL VON OSSIETZKY universität OLDENBURG

Wind turbine performance – WT_Perf (3/3)

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"
```

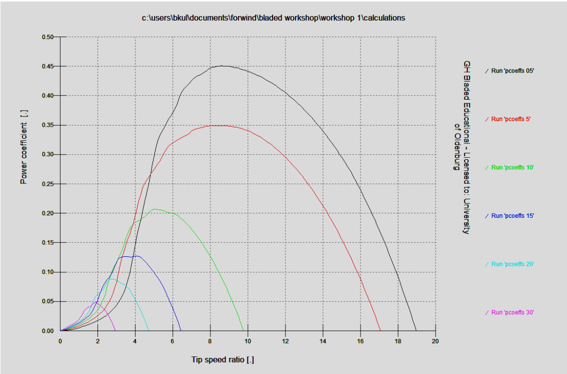
6

7

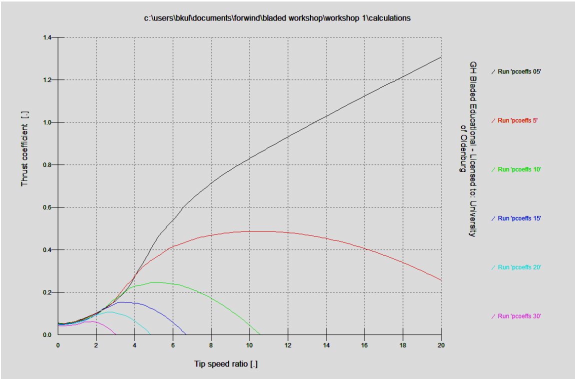
```
-----  Output Configuration  ------------------------------------------------
False                   UnfPower:                 Write parametric power to a
True                    TabDel:                   Make output tab-delimited (
1                       ConvFlag:                 For non-converging cases, (
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.  Er
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                    OutTrq:                   Request output of shaft tor
False                   OutFlp:                   Request output of flap bend
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              SpdSt, SpdEnd, SpdDel:    First, last, delta speeds.
```

Summary / Conclusion

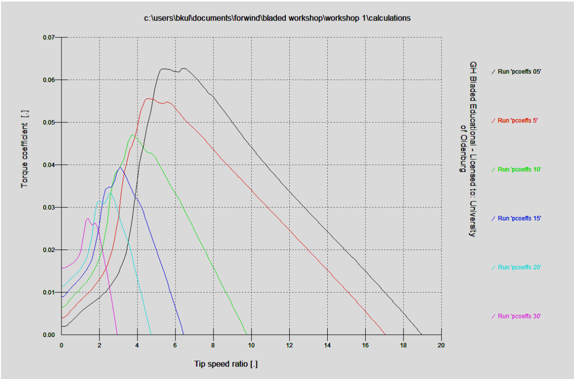
- We reviewed the previous design steps
- We discussed the use of dimensional and non-dimensional performance curves
- We calculated the performance curves with help of “WT_Perf”



Power coeff.



Thrust coeff.



Torque coeff.