

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

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Oldenburg, May 2016

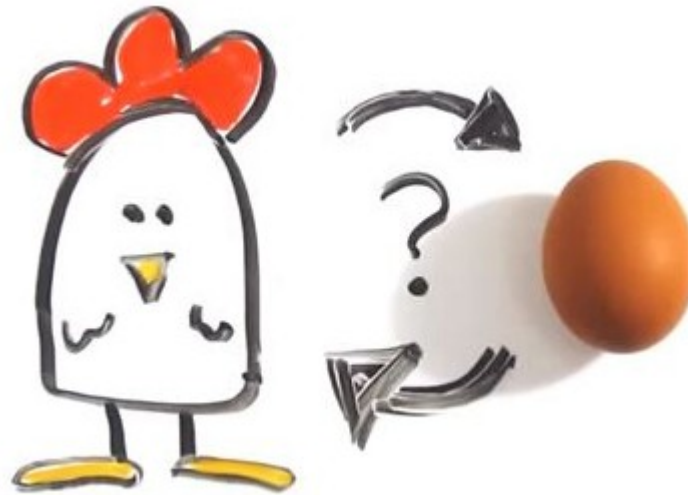
Prof. Dr. Martin Kühn

CIP Tutorials



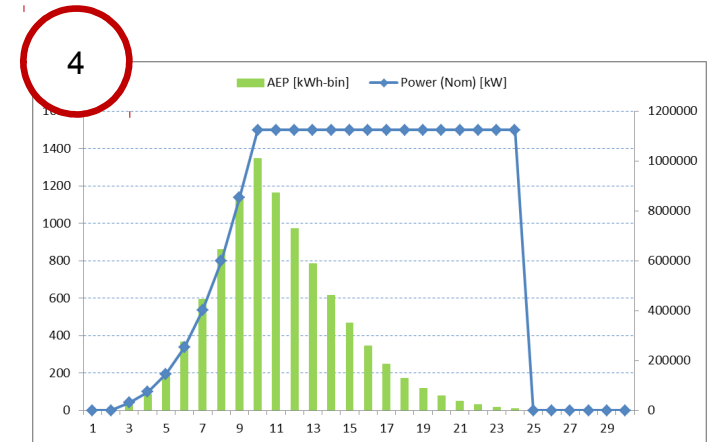
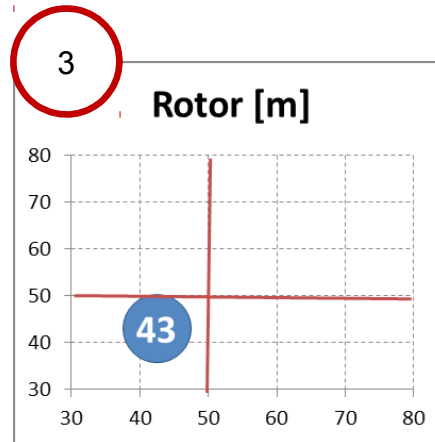
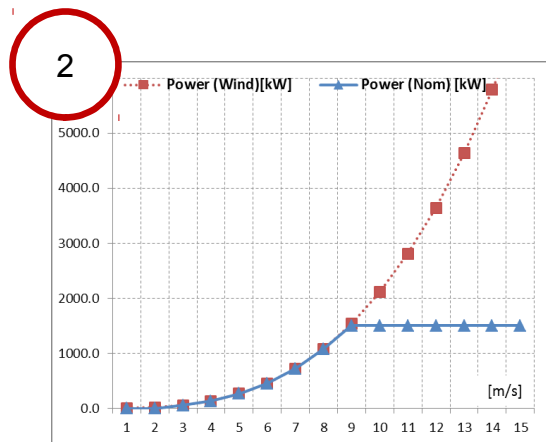
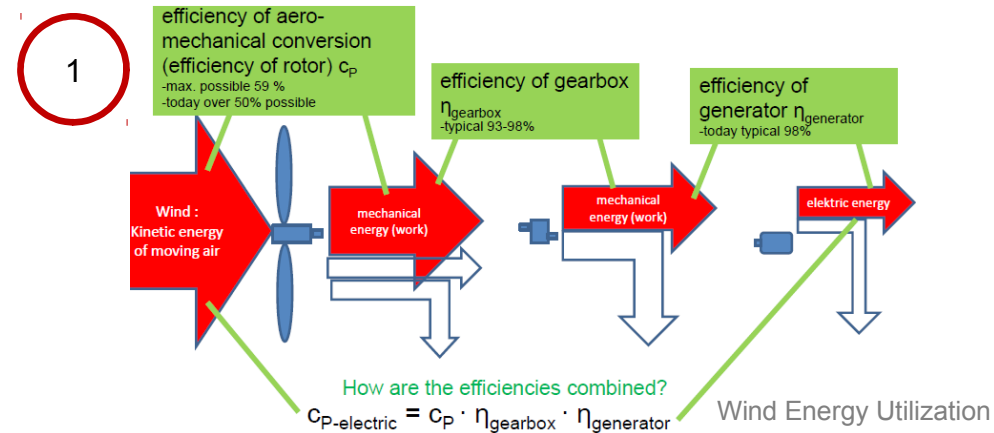
Previous design steps

- 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

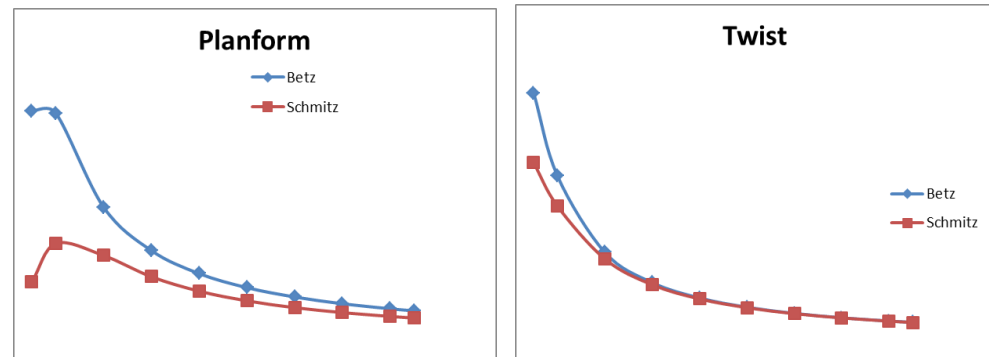
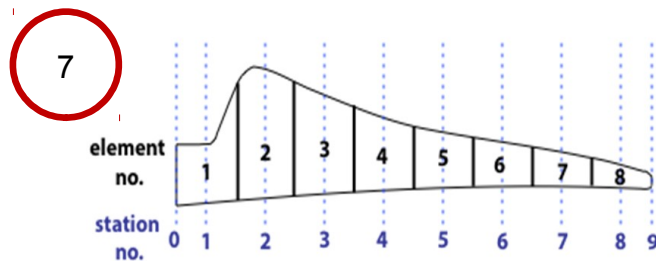


Previous design steps (2/3)

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

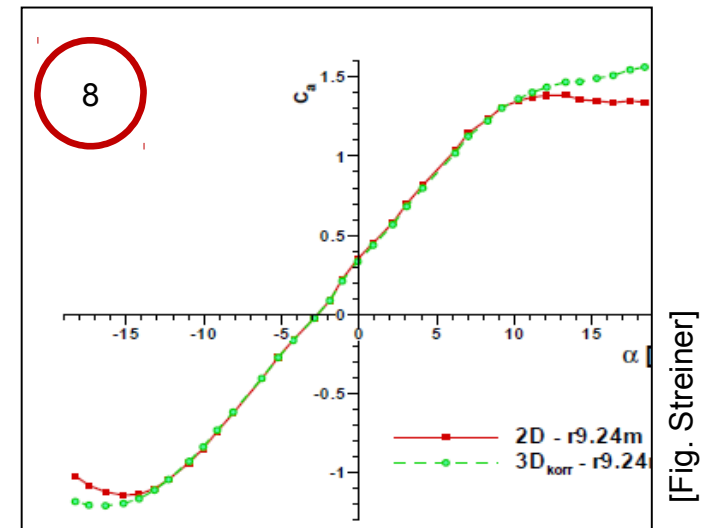
Airflow	Blue	Dark Blue	Green	Blue	Yellow	Pink	Pearlwhite	Orange	Black	Violet	Grey
1st	1	2	3	4	5	6	7	8	9	10	11
2nd	12	13	14	15	16	17	18	19	20	21	22
3rd	23	24	25	26	27	28	29	30	31	32	33
4th	34	35	36	37	38	39	40	41	42	43	44
5th	45	46	47	48	49	50	51	52	53	54	55
6th	56	57	58	59	60	61	62	63	64	65	66
7th	67	68	69	70	71	72	73	74	75	76	77
8th	78	79	80	81	82	83	84	85	86	87	88
9th	89	90	91	92	93	94	95	96	97	98	99
10th	100	101	102	103	104	105	106	107	108	109	110
11th	111	112	113	114	115	116	117	118	119	120	121
12th	122	123	124	125	126	127	128	129	130	131	132
13th	133	134	135	136	137	138	139	140	141	142	143
14th	144	145	146	147	148	149	150	151	152	153	154
15th	155	156	157	158	159	160	161	162	163	164	165
16th	166	167	168	169	170	171	172	173	174	175	176
17th	177	178	179	180	181	182	183	184	185	186	187
18th	188	189	190	191	192	193	194	195	196	197	198
19th	199	200	201	202	203	204	205	206	207	208	209
20th	210	211	212	213	214	215	216	217	218	219	220
21st	221	222	223	224	225	226	227	228	229	230	231
22nd	232	233	234	235	236	237	238	239	240	241	242
23rd	243	244	245	246	247	248	249	250	251	252	253
24th	254	255	256	257	258	259	260	261	262	263	264
25th	265	266	267	268	269	270	271	272	273	274	275
26th	276	277	278	279	280	281	282	283	284	285	286
27th	287	288	289	290	291	292	293	294	295	296	297
28th	298	299	300	301	302	303	304	305	306	307	308
29th	309	310	311	312	313	314	315	316	317	318	319
30th	320	321	322	323	324	325	326	327	328	329	330
31st	331	332	333	334	335	336	337	338	339	340	341
32nd	342	343	344	345	346	347	348	349	350	351	352
33rd	353	354	355	356	357	358	359	360	361	362	363
34th	364	365	366	367	368	369	370	371	372	373	374
35th	375	376	377	378	379	380	381	382	383	384	385
36th	386	387	388	389	390	391	392	393	394	395	396
37th	397	398	399	400	401	402	403	404	405	406	407
38th	408	409	410	411	412	413	414	415	416	417	418
39th	419	420	421	422	423	424	425	426	427	428	429
40th	430	431	432	433	434	435	436	437	438	439	440
41st	441										

angle of attack	coefficient C_L [-]	coefficient C_D [-]	coefficient $C_{L\alpha}$ [-]	drag ratio C_D / C_L [%]
0.00	0.000	0.000	0.000	0.000
0.010	0.010	0.000	0.77464	0.000
0.020	0.020	0.001	0.900	0.000
0.030	0.030	0.002	0.922	0.000
0.040	0.040	0.003	0.938	0.000
0.050	0.050	0.004	0.949	0.000
0.060	0.060	0.005	0.956	0.000
0.070	0.070	0.006	0.960	0.000
0.080	0.080	0.007	0.962	0.000
0.090	0.090	0.008	0.963	0.000
0.100	0.100	0.009	0.964	0.000
0.110	0.110	0.010	0.964	0.000
0.120	0.120	0.011	0.964	0.000
0.130	0.130	0.012	0.964	0.000
0.140	0.140	0.013	0.964	0.000
0.150	0.150	0.014	0.964	0.000
0.160	0.160	0.015	0.964	0.000
0.170	0.170	0.016	0.964	0.000
0.180	0.180	0.017	0.964	0.000
0.190	0.190	0.018	0.964	0.000
0.200	0.200	0.019	0.964	0.000
0.210	0.210	0.020	0.964	0.000
0.220	0.220	0.021	0.964	0.000
0.230	0.230	0.022	0.964	0.000
0.240	0.240	0.023	0.964	0.000
0.250	0.250	0.024	0.964	0.000
0.260	0.260	0.025	0.964	0.000
0.270	0.270	0.026	0.964	0.000
0.280	0.280	0.027	0.964	0.000
0.290	0.290	0.028	0.964	0.000
0.300	0.300	0.029	0.964	0.000
0.310	0.310	0.030	0.964	0.000
0.320	0.320	0.031	0.964	0.000
0.330	0.330	0.032	0.964	0.000
0.340	0.340	0.033	0.964	0.000
0.350	0.350	0.034	0.964	0.000
0.360	0.360	0.035	0.964	0.000
0.370	0.370	0.036	0.964	0.000
0.380	0.380	0.037	0.964	0.000
0.390	0.390	0.038	0.964	0.000
0.400	0.400	0.039	0.964	0.000
0.410	0.410	0.040	0.964	0.000
0.420	0.420	0.041	0.964	0.000
0.430	0.430	0.042	0.964	0.000
0.440	0.440	0.043	0.964	0.000
0.450	0.450	0.044	0.964	0.000
0.460	0.460	0.045	0.964	0.000
0.470	0.470	0.046	0.964	0.000
0.480	0.480	0.047	0.964	0.000
0.490	0.490	0.048	0.964	0.000
0.500	0.500	0.049	0.964	0.000
0.510	0.510	0.050	0.964	0.000
0.520	0.520	0.051	0.964	0.000
0.530	0.530	0.052	0.964	0.000
0.540	0.540	0.053	0.964	0.000
0.550	0.550	0.054	0.964	0.000
0.560	0.560	0.055	0.964	0.000
0.570	0.570	0.056	0.964	0.000
0.580	0.580	0.057	0.964	0.000
0.590	0.590	0.058	0.964	0.000
0.600	0.600	0.059	0.964	0.000
0.610	0.610	0.060	0.964	0.000
0.620	0.620	0.061	0.964	0.000
0.630	0.630	0.062	0.964	0.000
0.640	0.640	0.063	0.964	0.000
0.650	0.650	0.064	0.964	0.000
0.660	0.660	0.065	0.964	0.000
0.670	0.670	0.066	0.964	0.000
0.680	0.680	0.067	0.964	0.000
0.690	0.690	0.068	0.964	0.000
0.700	0.700	0.069	0.964	0.000
0.710	0.710	0.070	0.964	0.000
0.720	0.720	0.071	0.964	0.000
0.730	0.730	0.072	0.964	0.000
0.740	0.740	0.073	0.964	0.000
0.750	0.750	0.074	0.964	0.000
0.760	0.760	0.075	0.964	0.000
0.770	0.770	0.076	0.964	0.000
0.780	0.780	0.077	0.964	0.000
0.790	0.790	0.078	0.964	0.000
0.800	0.800	0.079	0.964	0.000
0.810	0.810	0.080	0.964	0.000
0.820	0.820	0.081	0.964	0.000
0.830	0.830	0.082	0.964	0.000
0.840	0.840	0.083	0.964	0.000
0.850	0.850	0.084	0.964	0.000
0.860	0.860	0.085	0.964	0.000
0.870	0.870	0.086	0.964	0.000
0.880	0.880	0.087	0.964	0.000
0.890	0.890	0.088	0.964	0.000
0.900	0.900	0.089	0.964	0.000
0.910	0.910	0.090	0.964	0.000
0.920	0.920	0.091	0.964	0.000
0.930	0.930	0.092	0.964	0.000
0.940	0.940	0.093	0.964	0.000
0.950	0.950	0.094	0.964	0.000
0.960	0.960	0.095	0.964	0.000
0.970	0.970	0.096	0.964	0.000
0.980	0.980	0.097	0.964	0.000
0.990	0.990	0.098	0.964	0.000
1.000	1.000	0.099	0.964	0.000



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

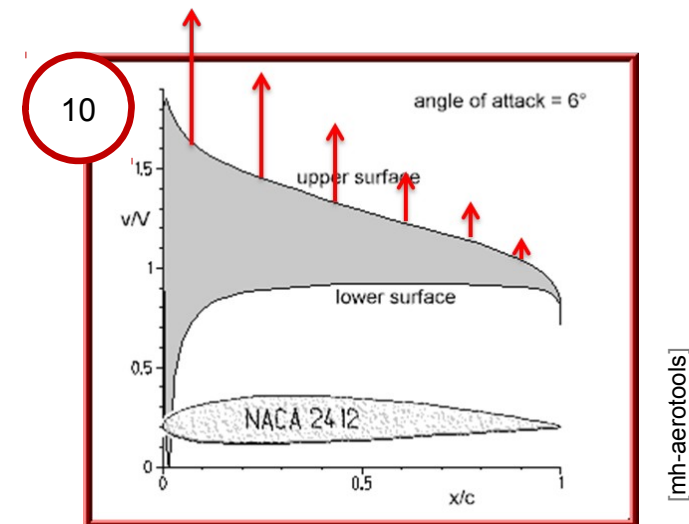


9

Neglected Effects

- Wake rotation
- Non-uniform induction factor over rotor disk
- Finite blade length
- Hub
- Stream tube blockage
- 3D effects
- Dynamics
- Yawed inflow

The block contains several small diagrams: a top-down view of a rotor disk showing wake rotation; a side view of a blade showing stream tube blockage; a 3D model of a turbine hub; a diagram of a yawed inflow; and a series of diagrams showing the evolution of a blade from a simple airfoil to a complex, twisted, and tapered design.



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: $c_s = 8/9$

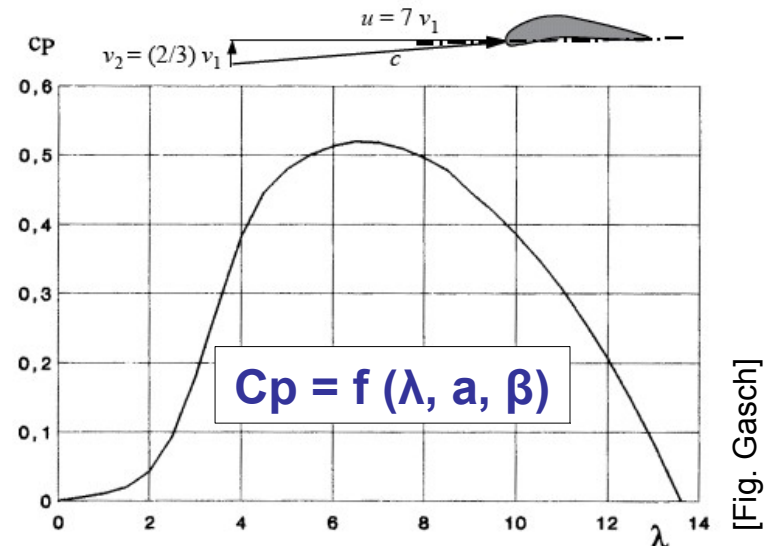
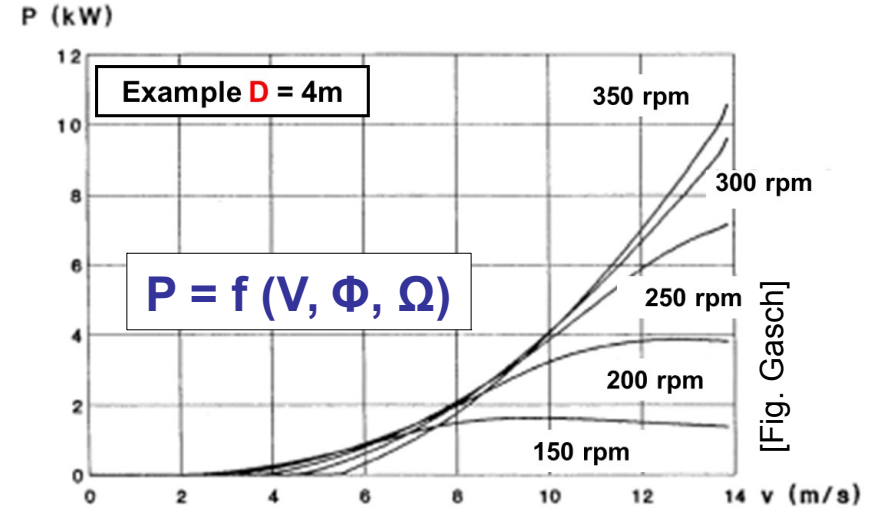
Dimensional & non-dimensional curves

Dimensional performance curves are:

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

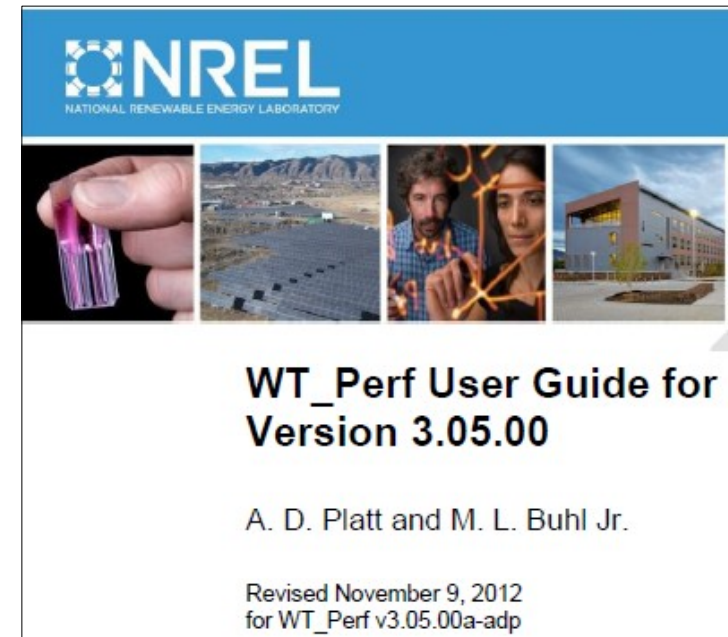
Non-dimensional performance curves are:

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



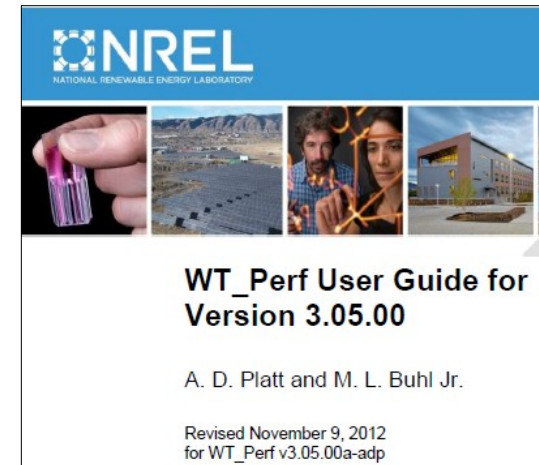
Performance curves – WT_Perf

- Overview
- Test case
- Wind turbine performance



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 algorithm
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

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

WT_Perf folder

3

```
Microsoft Windows [Version 6.1.7601]
Copyright (c) 2009 Microsoft Corporation. Alle Rechte vorbehalten.

C:\Users\Nopo>cd..
C:\Users>cd..
C:\>cd WT_Perf

C:\WT_Perf>WT_Perf WT_test.wtp
Using NWTC Subroutine Library (v1.05.01a, 8-Nov-2012).

Running WT_Perf (v3.05.00a-adp, 09-Nov-2012).

"Test" Wind turbine - file example for DoWES CIP Tutorial 03

Rotor speed = 22 rpm.
Rotor speed = 22.25 rpm.
Rotor speed = 22.5 rpm.
Rotor speed = 22.75 rpm.
Rotor speed = 23 rpm.
Rotor speed = 23.25 rpm.
Rotor speed = 23.5 rpm.
Rotor speed = 23.75 rpm.
Rotor speed = 24 rpm.

Main loop used 15.46 seconds of User CPU time.

WT_Perf terminated normally.

C:\WT_Perf>
```

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 0.001666 0.001666 0.001666 0
1.100 0.002665 0.002665 0.002665 0.002665 0.002665 0.002665 0.002665 0
1.200 0.003914 0.003914 0.003914 0.003914 0.003914 0.003914 0.003914 0
1.300 0.005430 0.005430 0.005430 0.005430 0.005430 0.005430 0.005430 0
1.400 0.007224 0.007224 0.007224 0.007224 0.007224 0.007224 0.007224 0
1.500 0.009348 0.009348 0.009348 0.009348 0.009348 0.009348 0.009348 0
1.600 0.011829 0.011829 0.011829 0.011829 0.011829 0.011829 0.011829 0
1.700 0.014728 0.014728 0.014728 0.014728 0.014728 0.014728 0.014728 0
1.800 0.018010 0.018010 0.018010 0.018010 0.018010 0.018010 0.018010 0
1.900 0.021641 0.021641 0.021641 0.021641 0.021641 0.021641 0.021641 0
2.000 0.025686 0.025686 0.025686 0.025686 0.025686 0.025686 0.025686 0
2.100 0.030201 0.030201 0.030201 0.030201 0.030201 0.030201 0.030201 0
2.200 0.035183 0.035183 0.035183 0.035183 0.035183 0.035183 0.035183 0
2.300 0.040684 0.040684 0.040684 0.040684 0.040684 0.040684 0.040684 0
2.400 0.046704 0.046704 0.046704 0.046704 0.046704 0.046704 0.046704 0
2.500 0.053279 0.053279 0.053279 0.053279 0.053279 0.053279 0.053279 0
2.600 0.060432 0.060432 0.060432 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  AFile  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)

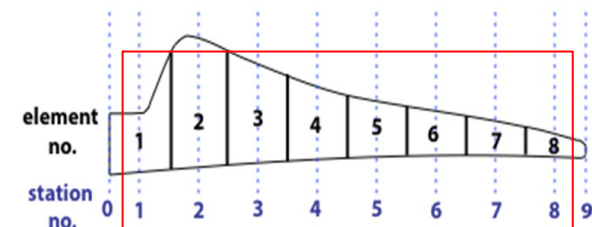
1. Comment 2-lines header for traceability: “color”, user & date
2. Select algorithms for calculation
3. Update “Turbine Data” section (if some are unknown, keep default)
4. Enter blade geometry (from CIP-01 file “*_start_parameters.xlsx”)
 - Relm – center of section
 - Afile – aerodynamic profile
 -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

5. Update the aerodynamic data

- NumAF – 2 airfoils
- Path to airfoils

```

----- Aerodynamic Data -----
1.225                               Rho:           Air density [mass/vol]
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. 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)

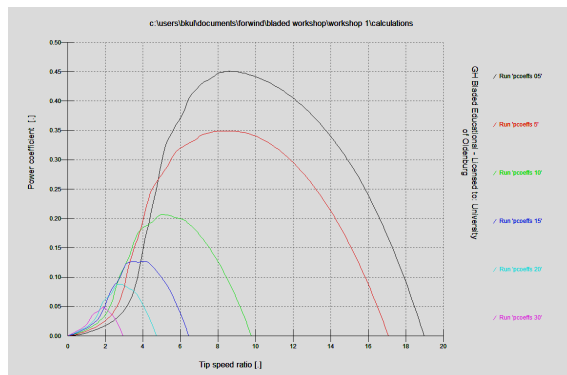
```

----- 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 n
"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 1
----- 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 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                        SpdSt, SpdEnd, SpdDel:   First, last, delta speeds.
    
```

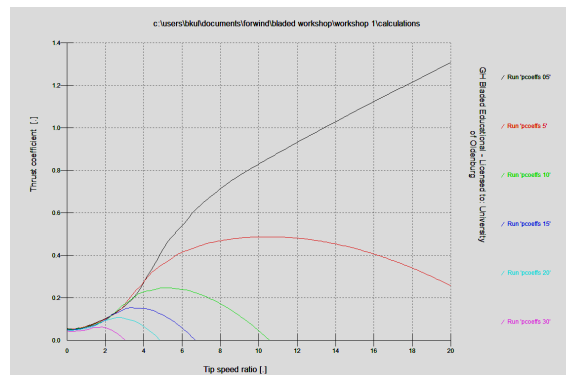
Note: Study results in spreadsheets

Summary / Conclusion

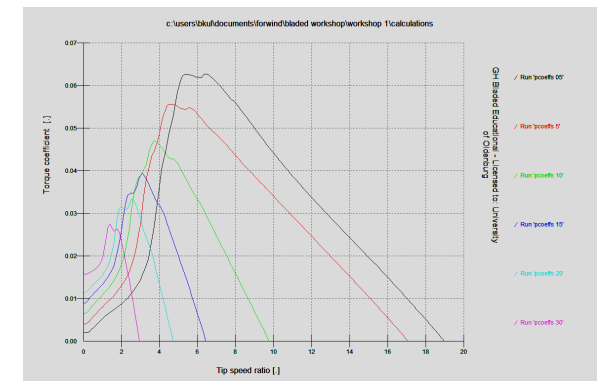
- We reviewed the previous design steps
- We discussed the use of dimensional and non-dimensional performance curves
- We calculated the performance curves with help of “WT_Perf”



Power coeff.



Thrust coeff.



Torque coeff.