Documentation of wind tunnel data

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1 Introduction

This is a documentation of measurement data used in [1, 2] and [3], which are results of a joint research program by the Norwegian University of Science and Technology (NTNU) in Trondheim and ForWind - Center for Wind Energy Research, University of Oldenburg. Wind tunnel experiments were performed using two different model wind turbines. We recorded full plane wake data with varying inflow conditions, angles of yaw misalignment and downstream distances. We would like to encourage researchers to use the data sets for validation or any other scientific purposes. Further documentation is given in the mentioned publications. Airfoil performance data computed with XFoil and 3D files of both turbines are uploaded with this document.
Flow velocity data were recorded using a two component Laser Doppler Anemometer (LDA). Both turbines are denoted *NTNU* and *ForWind*, respectively, with rotor diameters of $D_{NTNU} = 894\,\text{mm}$ and $D_{ForWind} = 580\,\text{mm}$. As described in [2], three different inflow conditions were investigated, at three angles of yaw misalignment γ. Table 1 gives an overview of the data availability. A positive yaw angle means a clockwise rotation of the rotor when observed from above.

Grid	Distance	γ [°]	Availability
uniform	$3D$	-30	none
uniform	$3D$	0	none
uniform	$3D$	+30	none
uniform	$6D$	-30	both
uniform	$6D$	0	both
uniform	$6D$	+30	both
shear	$3D$	-30	both
shear	$3D$	0	NTNU
shear	$3D$	+30	both
shear	$6D$	-30	both
shear	$6D$	0	both
shear	$6D$	+30	both
none	$3D$	-30	none
none	$3D$	0	none
none	$3D$	+30	none
none	$6D$	-30	NTNU
none	$6D$	0	NTNU
none	$6D$	+30	NTNU

Table 1: Summary of the data availability. The distance is the downstream from the rotor in mean flow direction. Availability refers to the respective turbine(s). For definitions of the turbulence grids and the yaw angle, please refer to [2, 1] and Section 2.3.

2 Experimental setup

2.1 Wind tunnel

The model turbines were tested in the closed-return wind tunnel at the Fluid Mechanics Lab at the Department for Energy and Process Engineering at NTNU in Trondheim. It has a test section which is 2.71 m wide and 11.15 m long. The tunnel has a flexible roof, which has been adjusted for zero pressure gradient at 10ms^{-1}. The tunnel heights are given in Table 2, Figure 2.1 shows a sketch of the wind tunnel setup, defining the coordinate system. Both turbines were installed at different positions in the wind tunnel: the NTNU turbine was placed 1.788 m from the inlet, the ForWind turbine 4.470 m. Both turbines have a hub height of 0.82 m. The measurement grid of the LDA is shown in Figure 4.

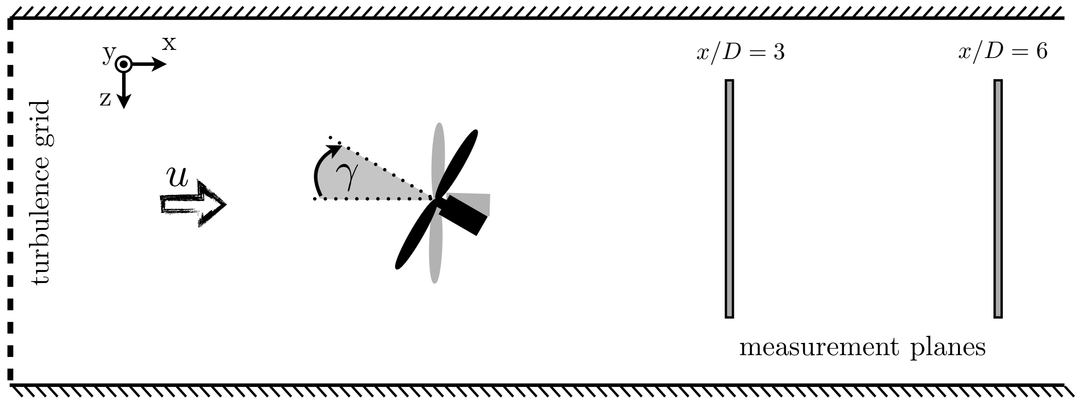

Figure 1: Sketch of the wind tunnel setup, top view. Scales do not match.

Distance from inlet [m]	Test section height [m]
0.000	1.801
2.810	1.801
5.621	1.813
8.435	1.842
11.150	1.851

Table 2: Test section heights as function of distance from the inlet.

2.2 Model wind turbines

Two intentionally different model wind turbines were used, which are described in [1, 2] and [3] in more detail. Table 3 shows an overview of chosen turbine specifics, Figure 2 shows sketches. Performance data of XFoil simulations are uploaded with this document. Further specifications such as airfoil and blade geometries are shown in the appendix.

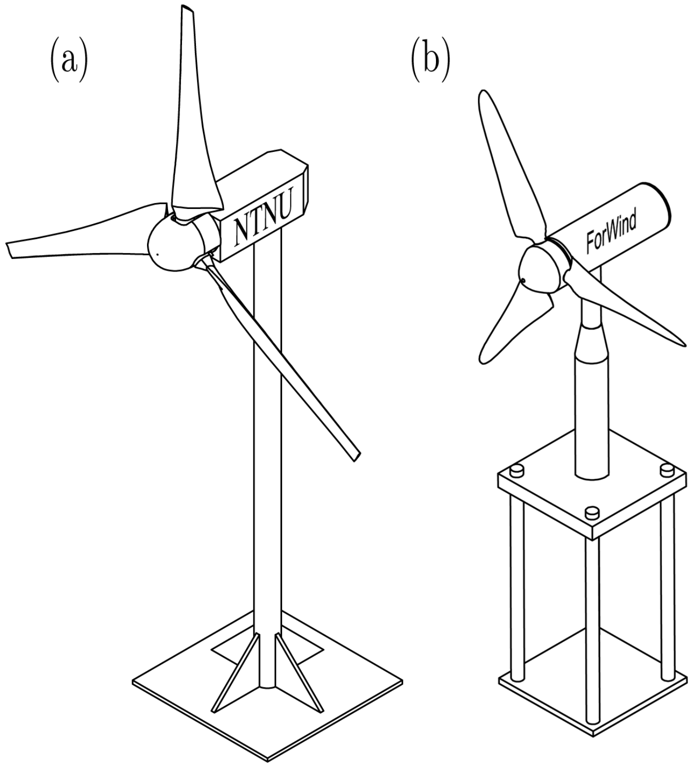

Figure 2: Sketches of both model wind turbines, (a) NTNU, (b) ForWind.

Turbine	Rotor diameter	Hub height	Blockage	TSR	Re_{tip}	Rotation	c_T
ForWind	0.580 m	0.82 m	5.4 %	6	$\approx 6.4 \times 10^4$	cw	0.87
NTNU	0.894 m	0.89 m	13 %	6	$\approx 1.1 \times 10^5$	ccw	0.87

Table 3: Summary of main turbine characteristics. The tip speed ratio (TSR) is based on the free stream velocity u_{ref} at hub height. The Reynolds number at the blade tip, Re_{tip}, is based on the chord length at the blade tip and the effective velocity during turbine operation. The blockage corresponds to the ratio of the rotor's swept area to the wind tunnel's cross sectional area. The direction of rotation refers to observing the rotor from upstream, with (c)cw meaning (counter)clockwise. The thrust coefficients were measured at $\gamma = 0°$ and corrected for the thrust on tower and support structures.

2.3 Inflow

Two different turbulence grids were used throughout the experiments, which are denoted *shear* grid and *uniform* grid, respectively. Additionally, measurements without any turbulence grid were performed as reported in [2]. The vertical velocity gradient is described by

$$u/u_{ref} = \left(\frac{y}{y_{ref}}\right)^{\alpha} , \qquad (1)$$

with α being the shear exponent and u_{ref} being the reference velocity in the free stream. Table 2.3 summarizes the inflow situations. The uniform grid is made of wooden bars of 44 mm × 44 mm cross section, having a solidity of 35 % and a mesh size of 240 mm, cf. [4]. The shear grid has a constant horizontal mesh width of 240 mm and varying vertical spacings as listed in Table 5.

Grid	Turbine	α	u_{ref} [ms^{-1}]	TI [%]
none	NTNU	0	10	0.23
uniform	NTNU	0	10	10
uniform	ForWind	0	7.5	5
shear	NTNU	0.11	10	10
shear	ForWind	0.11	7.5	5

Table 4: Definitions of the inflow velocities.

Bar number	Height [mm]
8	1600
7	1300
6	1015
5	795
4	575
3	385
2	203
1	40

Table 5: Vertical spacings of the shear grid. Measurements are from the wind tunnel floor.

3 The data

The data sets are available as binary Matlab files, `.mat`. Exemplary scripts for plotting the data are supplied as `*.m` files. The two component LDA recorded the mean flow component $\vec{u}$ and the vertical flow component $\vec{v}$, whereas a positive value refers to an upwards flow.

3.1 Mean data

The file `all_means.mat` contains averaged values along with some chosen quantities based on $\vec{u}$ and $\vec{v}$. Their definitions are given below.

$$
\begin{aligned}
\texttt{Umean} &= \langle \vec{u}(t) \rangle && (2)\\
\texttt{Vmean} &= \langle \vec{v}(t) \rangle && (3)\\
\texttt{TI1} &= \sigma_{\vec{u}(t)} / \langle \vec{u}(t) \rangle && (4)\\
\texttt{TI2} &= \sigma_{|\vec{u}\vec{v}|} / \langle |\vec{u}\vec{v}| \rangle && (5)\\
\texttt{TKE1} &= 0.5 \left(\langle u'(t)^2 \rangle + \langle v'(t)^2 \rangle \right) && (6)\\
\texttt{TKE2} &= 2/3 \left(\langle u'(t)^2 \rangle \right) && (7)\\
\texttt{TKE3} &= 0.5 \left(\langle u'(t)^2 \rangle + 2 \langle v'(t)^2 \rangle \right) && (8)\\
\texttt{NormalStress\_uu} &= \langle u'(t) u'(t) \rangle && (9)\\
\texttt{NormalStress\_vv} &= \langle v'(t) v'(t) \rangle && (10)\\
\texttt{ShearStress\_uv} &= \langle u'(t) v'(t) \rangle , && (11)\\
& && (12)
\end{aligned}
$$

whereas

$$\sigma_{\vec{u}(t)} = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} \vec{u}(t)^2} \ , \qquad (13)$$

$$u'(t) = \vec{u}(t) - \langle \vec{u}(t) \rangle \ , \qquad (14)$$

and

$$|\vec{u}\vec{v}| = \sqrt{\vec{u}(t)^2 + \vec{v}(t)^2} \ . \qquad (15)$$

$\langle \cdot \rangle$ denotes a mean value.
The file is set up as a structure of the form `turbine.turbulence_grid.distance.yaw_angle.quantity`, with

turbine: `NTNU` or `ForWind`

turbulence grid: `TurbGrid`, `ShearGrid` or `NoGrid`,

distance: `D3` or `D6`, corresponding to the downstream distances $x/D = 3$ or $x/D = 6$,

yaw angle: `neg30`, `zero` or `pos30`, referring to $\gamma = \{0°, \pm 30°\}$

quantity: one of the quantities as defined in Eq. (2)–(11). Additionally, the items `Ypos` and `Zpos` contain the respective y- and z- position in millimeters, (0/0) referring to the rotor center.

Exemplary, the mean velocity data $\langle \vec{u} \rangle$ $6D$ behind the ForWind turbine with a shear grid installed at a yaw angle of $\gamma = -30°$ are contained in the vector `ForWind.ShearGrid.D6.neg30.Umean`.

3.2 Visualization examples

The example code contained in `plot_means.m` shows a simple way to plot data based on the file `all_means.mat`. The contained code results in the plot shown in Figure 3. The function `wake_plot.m` is used for data interpolation and drawing the contours of the respective turbine. Further documentation is given within the code.

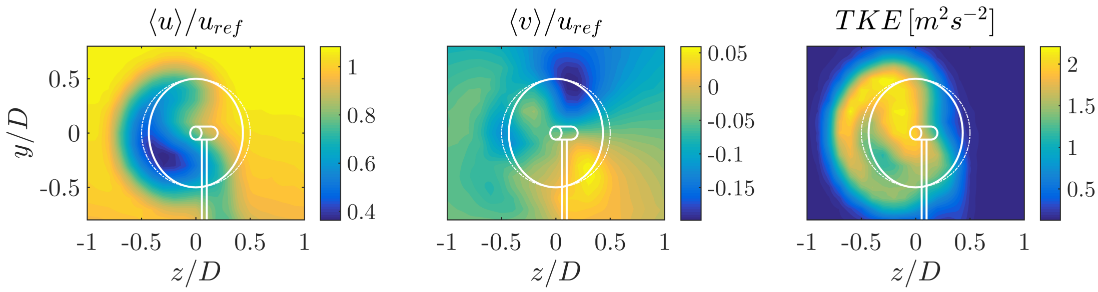

Figure 3: Exemplary plots of the wake 3D behind the ForWind turbine at $\gamma = 30°$. The graphs result of the example code `plot_means.m`.

3.3 Raw data

The raw data are contained in two seperate `*.mat` files for each turbines, `NTNU_timeseries.mat` and `ForWind_timeseries.mat`. Both files contain one cell variable for each wake with the name structure `turbine_grid_distance_yaw`, exemplary `ForWind_ShearGrid_6D_neg30` for the wake $6D$ behind the ForWind turbine with a shear grid installed at a yaw angle of $\gamma = -30°$. Each cell array is set up as follows:

{`:,1`}: y-position in mm

{`:,2`}: z-position in mm

{`:,3`}: 1D vector $\vec{u}(t)$

{`:,4`}: 1D vector $\vec{v}(t)$

{`:,5`}: 1D vector, time stamp in seconds

{`:,6`}: mean value of $\vec{u}(t)$

{`:,7`}: mean value of $\vec{v}(t)$

Exemplary, the time series $\vec{u}(t)$ at the 10^{th} measurement location of the previous example is accessed by `ForWind_ShearGrid_6D_neg30{10,3}`. The respective positions in mm are y=`ForWind_ShearGrid_6D_neg30{10,1}` and z=`ForWind_ShearGrid_6D_neg30{10,2}`.
The positions refer to the measurement grid shown in Figure 4.

4 Remarks

We encourage scientists to use the data. Please inform the authors if the data is used or for any further information.

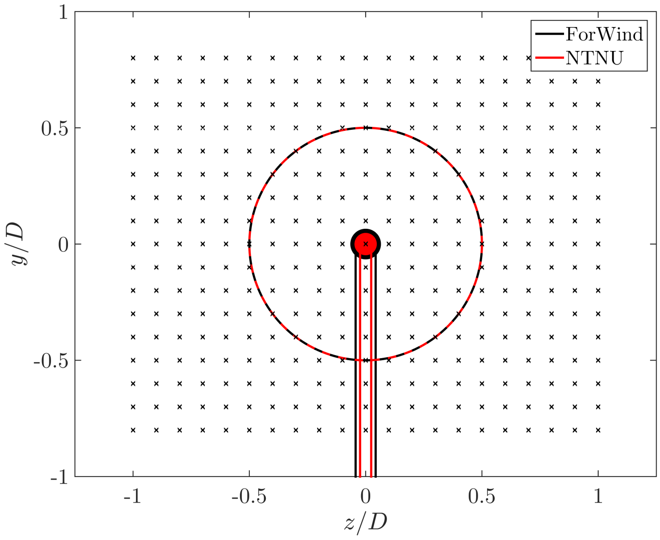

Figure 4: Dimensionless measurement grid, D=890 mm for the NTNU turbine and D=580 mm for the ForWind turbine. $y = z = 0$ corresponds to the rotor center. Lines show the turbine contours looking in mean flow direction, crosses mark measurement locations.

References

[1] Jannik Schottler, Franz Mühle, Jan Bartl, Joachim Peinke, Muyiwa S Adaramola, Lars Sætran, and Michael Hölling. Comparative study on the wake deflection behind yawed wind turbine models. *Journal of Physics: Conference Series*, 854:012032, may 2017.

[2] Jan Bartl, Franz Mühle, Jannik Schottler, Lars Sætran, Joachim Peinke, Muyiwa Adaramola, and Michael Hölling. Wind tunnel experiments on wind turbine wakes in yaw: Effects of inflow turbulence and shear. *Wind Energy Science Discussions*, (January):1–22, jan 2018.

[3] Jannik Schottler, Jan Bartl, Franz Mühle, Lars Sætran, Joachim Peinke, and Michael Hölling. Wind tunnel experiments on wind turbine wakes in yaw: Redefining the wake width. *Wind Energy Science Discussions*, (January):1–22, jan 2018.

[4] Jan Bartl and Lars Sætran. Blind test comparison of the performance and wake flow between two in-line wind turbines exposed to different turbulent inflow conditions. *Wind Energy Science*, 2(1):55–76, feb 2017.

A Technical drawings

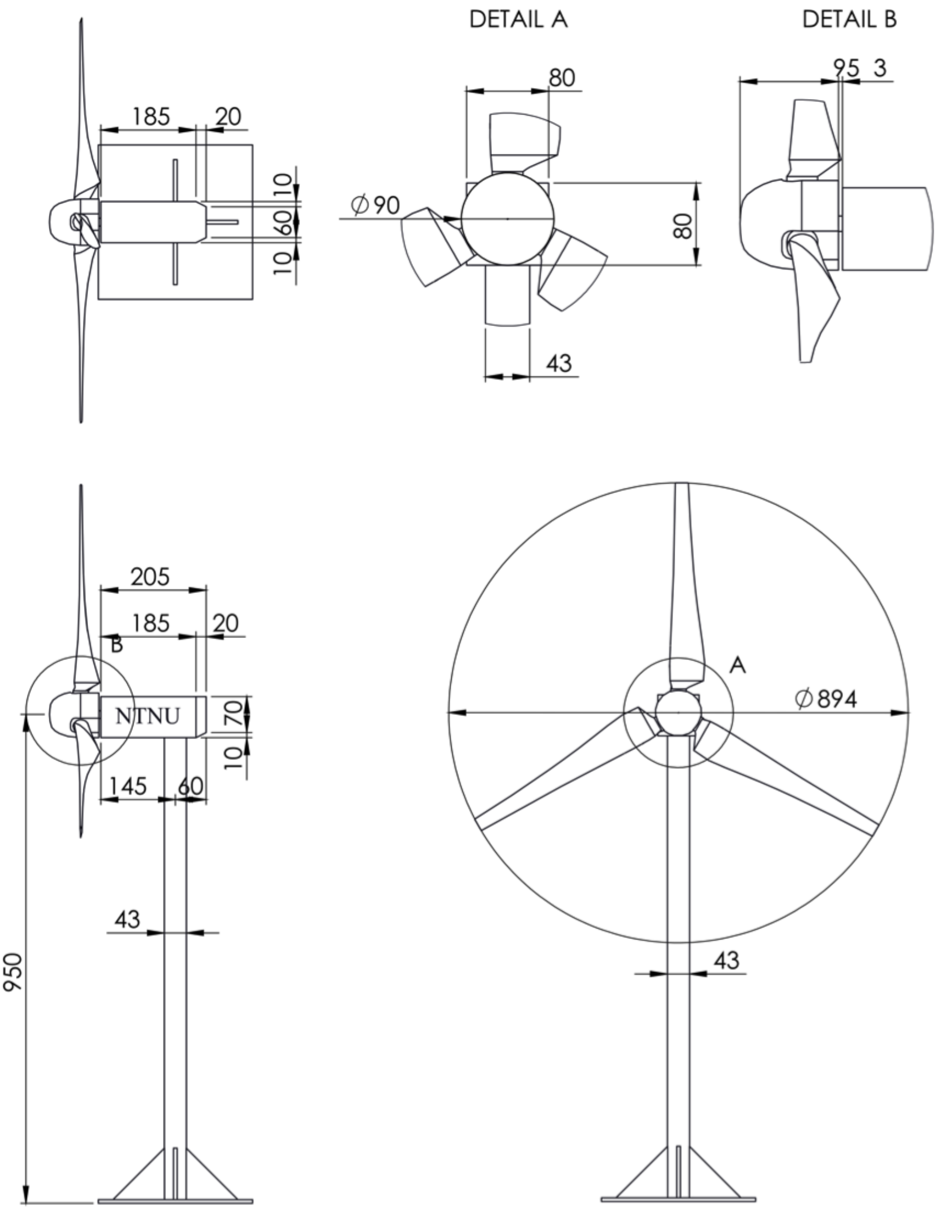

Figure 5: Technical drawings of the NTNU turbine, measures in mm.

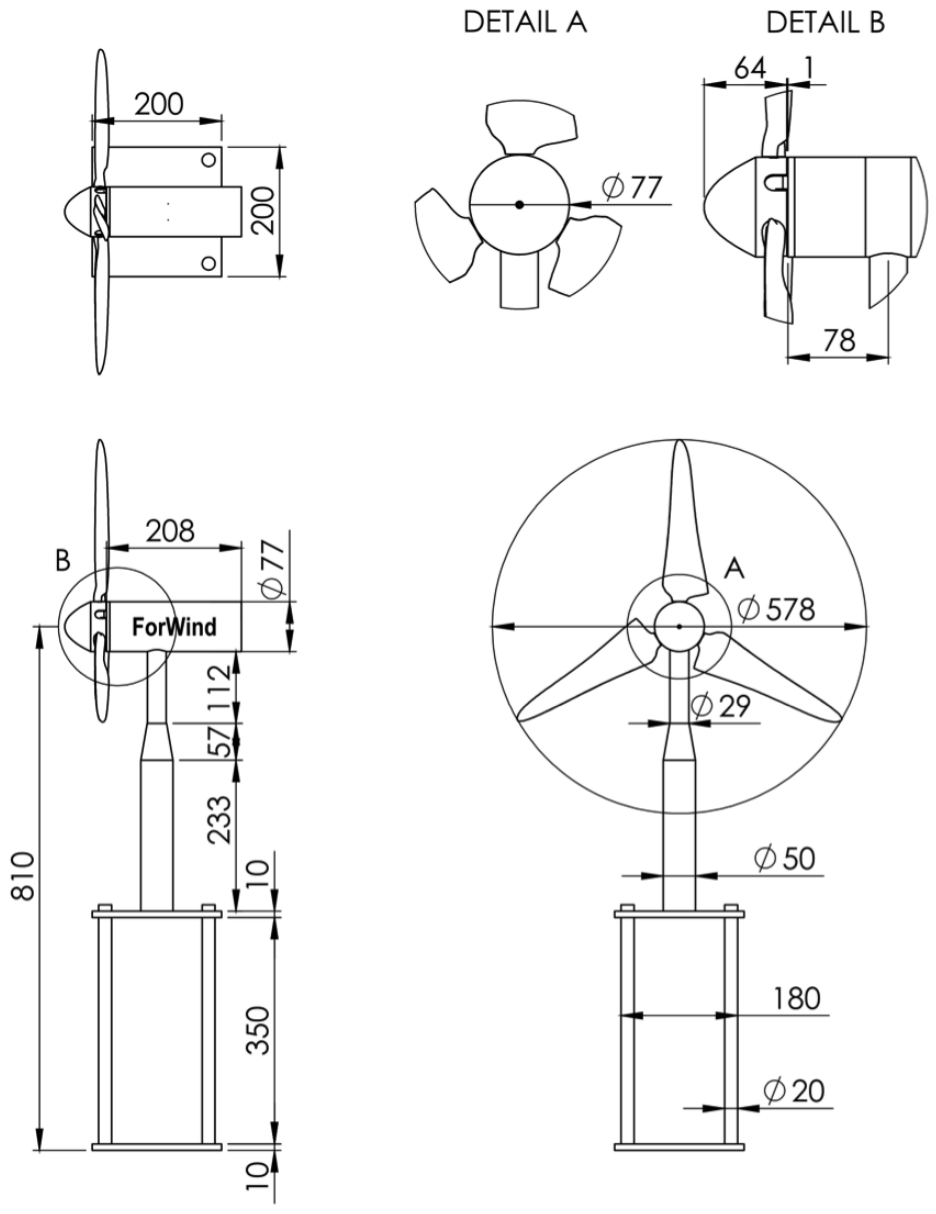

Figure 6: Technical drawings of the ForWind turbine, measures in mm.

B Airfoil geometries

x/c	y/c (upper surface)	x/c	y/c (lower surface)
0.00000	0.00000	0.00000	0.00000
0.00018	0.00159	0.00021	-0.00146
0.00255	0.00748	0.00093	-0.00274
0.00954	0.01638	0.00216	-0.00403
0.02088	0.02596	0.00367	-0.00525
0.03651	0.03580	0.01367	-0.01035
0.05636	0.04562	0.02920	-0.01518
0.08026	0.05519	0.04998	-0.01960
0.10801	0.06434	0.07580	-0.02362
0.13934	0.07288	0.10637	-0.02729
0.17395	0.08068	0.14133	-0.03091
0.21146	0.08758	0.17965	-0.03486
0.25149	0.09343	0.21987	-0.03855
0.29361	0.09807	0.26153	-0.04064
0.33736	0.10133	0.30497	-0.04051
0.38228	0.10294	0.35027	-0.03794
0.42820	0.10249	0.39779	-0.03280
0.47526	0.10005	0.44785	-0.02563
0.52324	0.09607	0.50032	-0.01720
0.57161	0.09094	0.55484	-0.00841
0.61980	0.08489	0.61055	-0.00015
0.66724	0.07816	0.66644	0.00699
0.71333	0.07095	0.72142	0.01254
0.75749	0.06341	0.77434	0.01621
0.79915	0.05572	0.82409	0.01784
0.83778	0.04798	0.86953	0.01741
0.87287	0.04029	0.90945	0.01498
0.90391	0.03262	0.94257	0.01113
0.93072	0.02479	0.96813	0.00689
0.95355	0.01695	0.98604	0.00324
0.97251	0.00982	0.99655	0.00084
0.98719	0.00431	1.00000	0.00000
0.99668	0.00103	-	-
1.00000	0.00000	-	-

Table 6: NTNU turbine: NREL S826.

x/c	y/c (upper surface)	x/c	y/c (lower surface)
0.00127	0.00438	0.00438	-0.00186
0.00697	0.01172	0.01172	-0.00741
0.01702	0.01932	0.01932	-0.01285
0.03130	0.02677	0.02677	-0.01759
0.04978	0.03372	0.03372	-0.02141
0.07244	0.03993	0.03993	-0.02438
0.09921	0.04526	0.04526	-0.02660
0.12993	0.04961	0.04961	-0.02809
0.16442	0.05292	0.05292	-0.02888
0.20240	0.05518	0.05518	-0.02900
0.24358	0.05639	0.05639	-0.02852
0.28760	0.05658	0.05658	-0.02752
0.33405	0.05581	0.05581	-0.02608
0.38250	0.05415	0.05415	-0.02428
0.43249	0.05171	0.05171	-0.02217
0.48350	0.04859	0.04859	-0.01980
0.53499	0.04494	0.04494	-0.01723
0.58641	0.04086	0.04086	-0.01450
0.63717	0.03649	0.03649	-0.01167
0.68673	0.03197	0.03197	-0.00887
0.73449	0.02744	0.02744	-0.00628
0.77985	0.02304	0.02304	-0.00403
0.82224	0.01884	0.01884	-0.00220
0.86112	0.01494	0.01494	-0.00082
0.89600	0.01139	0.01139	0.00008
0.92639	0.00824	0.00824	0.00052
0.95193	0.00547	0.00547	0.00057
0.97235	0.00310	0.00310	0.00037
0.98745	0.00132	0.00132	0.00011
0.99681	0.00031	0.00031	0.00000
1.00000	0.00000	-	-

Table 7: ForWind turbine: SD7003.

C Blade geometries

Blade element	Radius [mm]	Chord [mm]	Twist [deg]
1	7.5	13.500	120.0
2	22.5	13.500	120.0
3	49.0	13.500	120.0
4	55.0	49.500	38.0
5	67.5	81.433	37.1
6	82.5	80.111	32.5
7	97.5	77.012	28.7
8	112.5	73.126	25.3
9	127.5	69.008	22.4
10	142.5	64.952	20.0
11	157.5	61.102	18.0
12	172.5	57.520	16.3
13	187.5	54.223	14.7
14	202.5	51.204	13.1
15	217.5	48.447	11.8
16	232.5	45.931	10.8
17	247.5	43.632	9.8
18	262.5	41.529	8.9
19	277.5	39.601	8.0
20	292.5	37.831	7.3
21	307.5	36.201	6.6
22	322.5	34.697	5.9
23	337.5	33.306	5.3
24	352.5	32.017	4.7
25	367.5	30.819	4.1
26	382.5	29.704	3.5
27	397.5	28.664	2.9
28	412.5	27.691	2.2
29	427.5	26.780	1.1
30	442.5	25.926	-0.7

Table 8: Blade geometries of the NTNU turbine.

Blade element	Radius [mm]	Chord [mm]	Twist [deg]
1	0	51.237	20.15
2	10	68.684	16.74
3	20	69.535	14.91
4	30	67.229	12.97
5	40	64.467	11.14
6	50	61.566	9.48
7	60	58.754	8.06
8	70	56.038	6.79
9	80	53.463	5.62
10	90	51.065	4.69
11	100	48.856	3.78
12	110	46.825	3.00
13	120	44.961	2.38
14	130	43.221	1.79
15	140	41.595	1.26
16	150	40.043	0.79
17	160	38.515	0.39
18	170	36.963	0.04
19	180	35.323	-0.29
20	190	33.457	-0.57
21	200	31.212	-0.82
22	210	28.320	-1.03
23	220	24.335	-1.34
24	230	18.216	-1.60
25	240	3.876	-1.79

Table 9: Blade geometries of the ForWind turbine. Notice that blade element 25 corresponds to the blade tip.