# An open source FORTRAN90 Code for aerodynamic design of wind turbine blades - V4 *

M. Korjahn, bewind GmbH, Rendsburg, Germany
A.P. Schaffarczyk, Kiel University of Applied Sciences, Kiel, Germany
D. Schlipf, Flensburg Unversity of Applied Sciences, Germany
contact: Alois.Schaffarczyk@FH-Kiel.de

Version 4: October 8, 2025

**Abstract**

A specific aerodynamic design methodology has been implemented into an open source FORTRAN90 code. It is available via github: `https://github.com/Schaffarczyk/KSS/`



*CFD Lab Report No, 128, Kiel, Germany

# Contents

# List of Figures

# List of Tables

# 1 Introduction

Here we report on an independent FORTRAN 90/95 (F90 for short) implementation of a purely aerodynamic wind turbine blade design methodology. It is intended to be as detailed as possible although a fair amount of knowledge of wind turbine aerodynamics is necessary, see, for example, [25, 23, 22]. Some - but not all - needs form a more practical point of view (maximum chord and twist, etc.) have been taken into account. This is in contrast to [10] who tried to find out what maximum $c_P$ may be reached without any restrictions by *practicability*.

Our basis, a lecture of Korjahn [12], presents a so-called two-point design. In a first attempt, however, we only describe an implementation of the first part: to reach at a blade with as large parts with optimum a(r) [1] as possible. *Design point 2* consists of a certain safety against gusts corresponding to stalled parts on the blade. Therefore the AOA has to have some safety-margin against this AOA-stall.

Main objectives of our approach are:

- understand and formalize the approach and
- compare to other codes.

Further or additional sources from

1. Korjahn [12],
2. Bak [1],
3. Schmitz [23] and
4. Johansen et al. [10].

are recommended to complement understanding.

<u>**Important:**</u> The code is by no means fool-proof:

**Bugs** may still be present.

**Input** data and esp. the aerodynamic one has to be checked as far as possible before its use.



# 2 The Blade-Element Momentum (BEM) formulation

## 2.1 General

(Conservation of) momentum on independent annular rings[25, 17, 20] serves as the fluid mechanical foundation. Key elements of a complete BEM formulation are

[1] Usually the term Betz-optimum is related to a(r) = 1/3 = const. Very recently [9] it has been shown that including wake-rotation and tip-loss a somewhat different distribution results: Close to the hub $a \to 0.25$ and close to the tip $a \to 0.4$.

already discussed in [5] and further refined in classical text from Wilson et al. [20] and de Vries [17], for example. Any applied aerodynamic wind turbine investigation uses it and it is still today regarded as the *work horse*. CFD can hardly claim to be more accurate although a large number of assumptions inherent to the BEM model have been overcome by this very different approach. The most recent analysis of the BEM-method is given in [7] with some focus on mathematical rigor and optimization.

## 2.2 Multiple Solutions of the BEM-Equation

It was already recognized by Wilson et al [20] p 108 ff. that under some specific circumstances the BEM-equations may not produce unique solutions. Maniaci [3] and Ning [21] further elaborate on this subject. To give an example, Fig. 1 (for a special section of a special commercial blade) shows the local thrust coefficient $cT_{loc}$ as function of a, the axial induction, defined by $u_1 := (1-a) \cdot U_{-\infty}, 0 \leq a \leq 0.5$. Momentum balance gives

$$c_T = 4a \cdot (1-a) \,, \tag{1}$$

whereas the counter-force from lift is its proper projection into the direction of the wind. Note, that this is a approximate description only, as $a'$ (circumferential induction) is neglected as well as tip-correction (see section 2.3) and a correction of $c_T$for larger a values of a ($a > a_c$), see section 2.4.

Our investigation for a 20 MW blade of 133 m length confirm this. It was recognized that the traditional fixed-point iteration did then not converge but simply jumps between two different values.

As a consequence we improved our implementation and search algorithms as follows:

- Firstly, scan the whole a-region $0 \leq a < 1$ in steps of 0.01. If there are solutions found by a binary search algorithm,
- start using standard fixed-point iteration until a maximum of number is reached
- switch to Newton(-Raphson) to to more iterations, if no convergence is reached:
- use a binary search algorithm *rtbis* from [18]

Fig. 2 shows an example. Therefore the argument of [20], p. 31

> As a guiding principle, itis suggested that the solution to be chosen in the case of multiple solutions is the one that maintains continuity of angle of attack along the blade span.

can be confirmed.

## 2.3 Tip-correction

Momentum theory is valid only for an infinite number of blades B $\to \infty$. As in most designs B is small ($B < 4$) this has to be taken into account. Indeed, as was shown

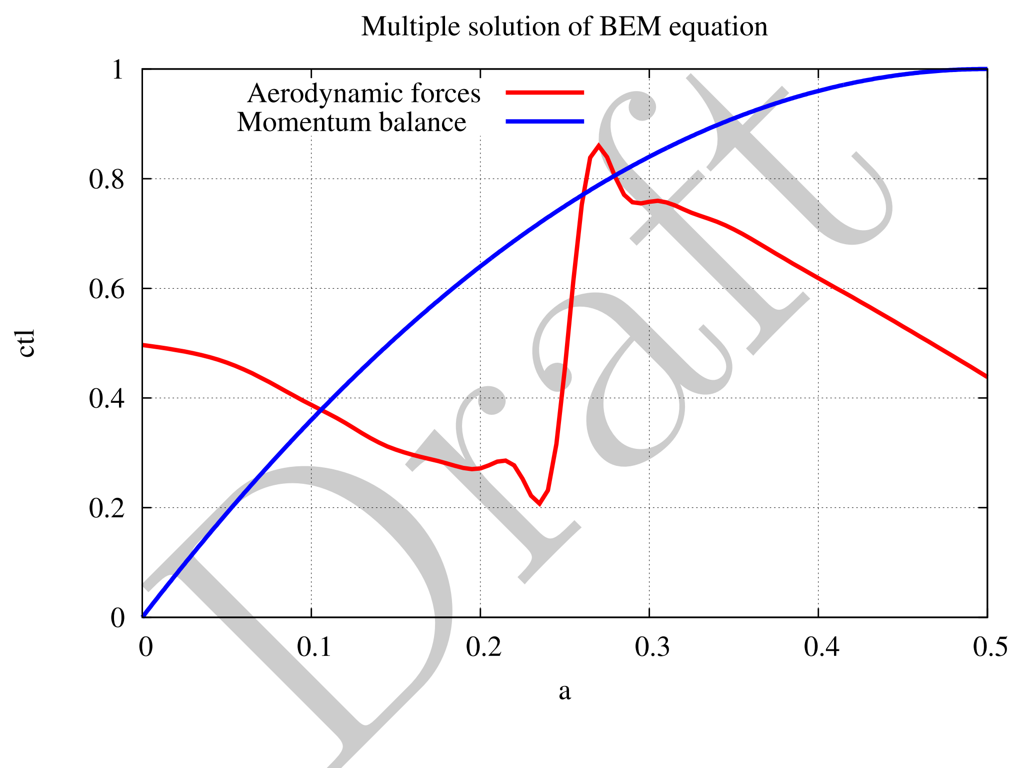


Figure 1: Example of distributions of multiple solutions from balancing aerodynamic (lift) forces and local (axial) momentum.

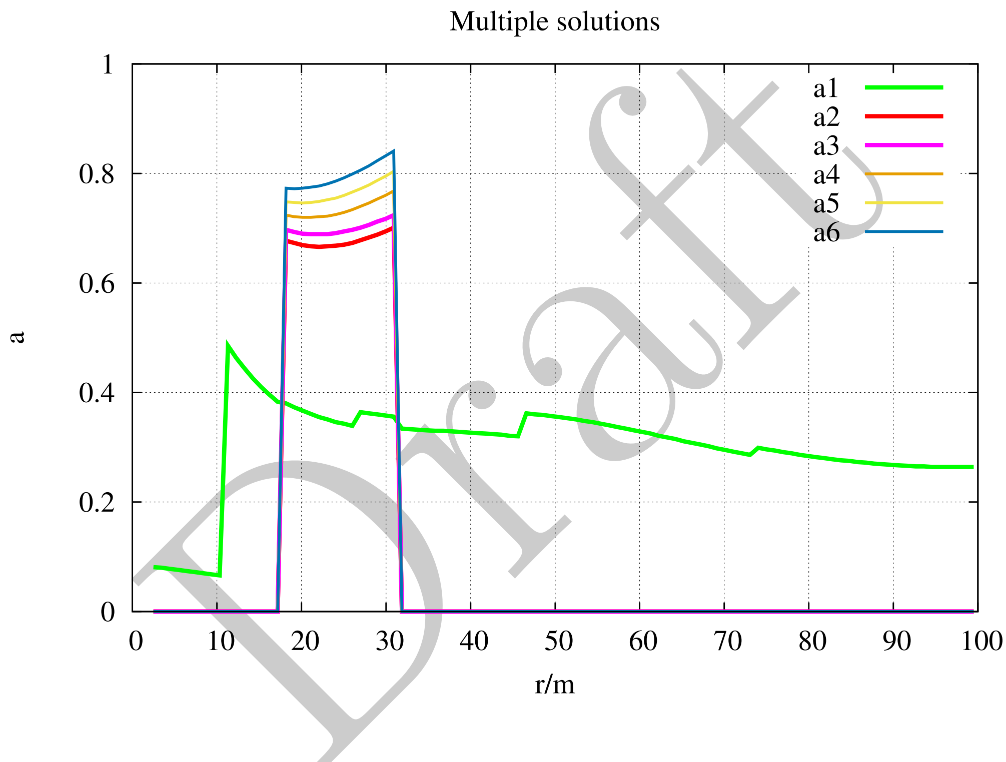


Figure 2: Example of how a binary search algorithm finds multiple solution along a whole blade (CIG10MW)

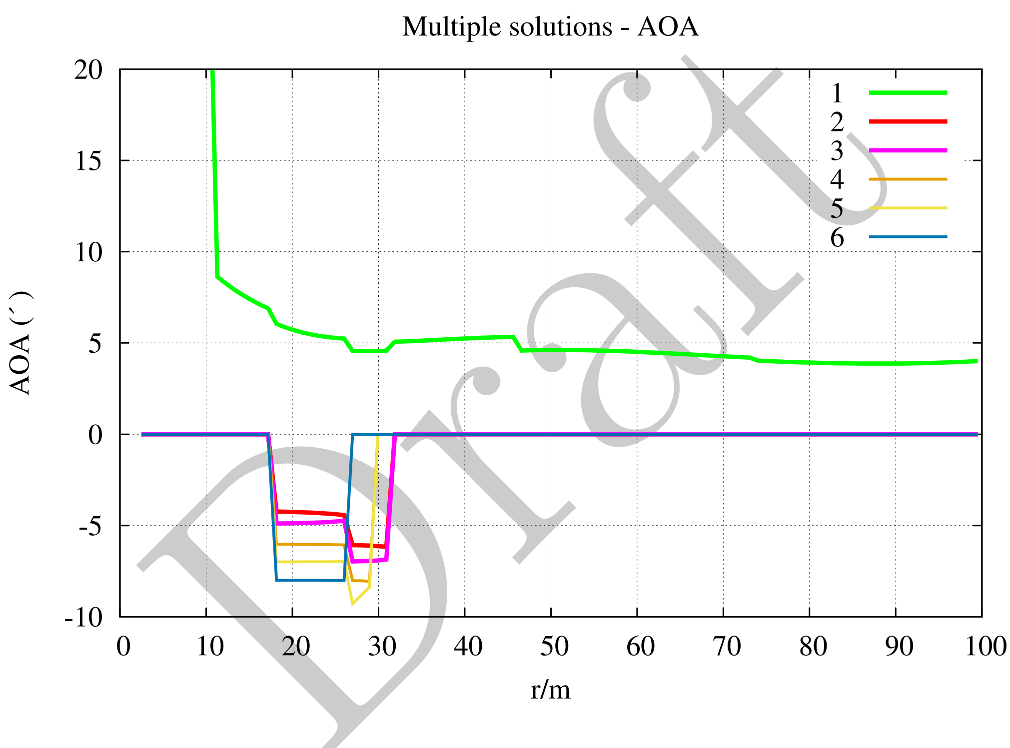


Figure 3: Variation of Angle of Attack (CIG10MW)

very early *tip losses* are as large as profile drag and must be accurately embedded into the code. Traditionally, the simplest (and oldest) version uses a factor F, which reduces circulation to zero when $r \rightarrow r_{tip}$:

$$F = \frac{2}{\pi} arccos \left( exp \left[ - \frac{B/2(1 - r/R_{tip}}{r/R_{tip} sin(\varphi)} \right] \right) \ . \tag{2}$$

Here, $\varphi$ is the all-important flow angle defined by

$$\tan(\varphi) = \frac{1 - a}{\lambda(1 + a')} \ , \tag{3}$$

which refers to $\lambda = \omega \cdot r / U_{-\infty}$ the local Tip-Speed-Ratio (TSR). $\omega = RPM \cdot \pi/30$ is the angular velocity.

### 2.4 Glauert Correction $cT(a)$ for $a > a_c$

It is further well known:

- Momentum theory is valid for $0 \leq a \leq 0.5$ only, and
- for some $a_c$ Eq. 1 becomes inaccurate.

To some extent this can be cured by *empirical engineering* extensions which are listed, for example in [7], Table 2.1. In principle at some $a_c = 0.33...0.4$ a more or less linear curve is attached to Eq. (1) so that $c_t(a = 1)$ approaches (somehow) 2 for $a \rightarrow 1$.

### 2.5 Sign convention

Sign issues esp. for the pitch are notorious. Following our basic interpretation

$$\alpha \text{ (AOA) } = \varphi \text{ (flow angle) } - \vartheta \text{ (twist] } , \tag{4}$$

we define **pitch** as being added to twist.

## 3 Code Description

### 3.1 A short note on FORTRAN

We will not defend ourselves why we use the *Grandfather of all (higher) programming languages* but only use it. It has been tried to write a code as simple as possible to make understanding and changes **(i.e. maintainability)** as simple as possible. A minimum set of algorithmic features is used. Especially, no tricks from Computer Science have be used. This code was(is) developed using *gfortran*, version 4.8.5 from 2015, see section 3.7. A more detailed description is given in [14].

## 3.2 Numerical Approach

Everybody knows from own experience the NEWTON-(Raphson) method for finding zeros of functions ($f(x_0) = 0$) or SIMPSON's rule for 1D-Integration. The ultimate manifestation of numerical algorithms may be found in the famous (series of) text book(s): *NUMERICAL RECIPES in Fortran 77* [18]. From here we have copied

1. SPLINE and
2. SPLINT.

Unfortunately, some overshooting at sharp corners might still be possible. *Bezier* polynomials were coded independently from its definition see [15].

## 3.3 Main program

*KKS.f* contains the main code. Its is merely a collection of routine-calls for set-up and definition of the course of investigation:

1. (dynamic) memory allocation,
2. Read *machine.in*,
3. Read in spline thickness distribution from *ThickDis.in*,
4. Analyze a given set of profiles, L2D-max.
5. If design-mode is chosen:
6. An initial BEM calculation is performed and
7. chord and twist might be (Bezier-) smoothed or
8. Twist may changed to improve $c_P$, see section 6.1 .



## 3.4 Memory mangement

*mem.f* defines all GLOBAL data. To use each module must start with a

*use mem*

command line.

## 3.5 Subroutines

1. BEM: Bem iteration as described in [22],
2. ANALYSIS: Analyse a blade described in *BlaDes.in* using routine *BEM*,
3. DESIGN: Determines chord and twist by given profiles and Betz [22], optimum criteria. See section 6.1 for more information about optimization.,

4. AIRFOILS: searches given $\alpha, c_L, c_D$ data for maximum of $c_L/c_D$, $c_{L,max}$ and slope at zero lift.

5. TipShapeEL: defines an elliptic (vertical tangent) tip shape geometry,

6. TipShapePara: defines an parabolic tip shape geometry determined by smooth slope at the beginning of the tip region and zero chord at tip.

7. BEZIER: smooting of a given data set according to the definition of Bezier polynoms,

8. smoothCHORD: smooths chord with subroutine BEZIER,

9. smoothTWIST: smooths twist with subroutine BEZIER,

10. improveTWIST: (1)tries to get locally as close as possible to 1/3 by adaption of twist, see Eq. 9. (2) J.N. Sørensen's approach, (3) a *constant circulation* approach

## 3.6 Functions

1. FNOVERK: (*(Real) Function N Over K*) calculates Binomial coefficients (BC) needed in BEZIER, (special numerical care has to be take because of strong growth of BCs),

2. FPR: Prandtl's tip loss F, see [22],

3. FBu: Burton's tip loss, see [19, 2],

4. chDES: optimum chord distribution from Betz (or Sch,mitz, or Glauert) [25],

5. chBe: Betz optimum chord, $a' \equiv 0$,

6. chSc: Schmitz optimum chord, $a'$ is included,

7. TWIST: twist (in deg) from Betz, $a = 1/3$ and $a' = 0$, so only local TSR enters,

8. AHANSEN: gives Glauert's correction as stated in [6],

9. ANREL: gives Glauert's correction as stated in [13].

$$c_T(a) = \frac{8}{9} + \left(4F - \frac{40}{9}\right) a + \left(\frac{90}{9} - 4F-\right) \cdot a^2 \,. \tag{5}$$

10. thickpoly: cubic interpolation of thickness

11. twistbend: simple table for inlclusion of twist-bend

12. apot: (1) Betz, (2) J.N. Sørensen, (3) constant circulation (very approximate)

## 3.7 Compilation

### 3.7.1 LINUX

For compilation we prefer use (in a SUSE-LINUX environment): [14] with mandatory options (see **compDesCode.cmd**):

-fno-automatic helps to resolve notorious issues with local variables in SUBROUTINES and FUNCTIONS

-fbounds-check to avoid not allowed memory access

-O3 high optimization

A typical job with 100 section and $100 \times 100$ wind-speed and pitch variation takes a few minutes on our simple *Intel(R) Core(TM) i3-4160 CPU @ 3.60GHz* CPU.

### 3.7.2 Windows

minGW (= minimum gcc for Windows) was used to compile a windows executable file. It is also available

## 3.8 Modularization

Apart from mem and KKS the following modules

- mem.f, declares global variables,
- Sub.f, a set of used subroutines and functions,
- SubNum.f, numerical functions: SPLINE and SPLINT from [18],

help to put some structure into the code.

## 3.9 Work Flow

All input has to be provided as ASCII files, as well as all output will be provided in the same format. Post-processing then has to be performed by other tools. We prefer GNUPLOT [16, 8] see section 4.2.

# 4 Output Files and Tools for Visualization

## 4.1 Description of Output Files

- *Bem.out*: sectional output from BEM, see table 5,
- *des.out*: sectional output from design: rsec, twist, chird, thick, $c_L^{des}$ and $AOA_{des}$,
- *ProProp.out*: from routine AIRFOILS: design properties of given airfoil data.

## 4.2 Description of GNUPLOT scripts

- *a.gpl*: plots a(r). data from Bem.out
- *chord.gpl*: plots c(r). data from Bem.out an BlaDes.in and des.out
- *cL-aoa.gpl* and *cL-cD.gpl*: plots polars. data from **.aer*
- *cL-des.gpl* plots $c_L^{des}$(r). data from *PrOpt/Bem.out*
- *twist.gpl*: plots $\vartheta$(r). data from Bem.out an BlaDes.in and des.out
- and some more

# 5 Mode: Analysis

## 5.1 Input data



The code is able to operate in two modes:

1. Design mode, set bit *DesMode* to .T. in file *Machine.in*,
2. if not, then the code will operate to analyze a given blade.

Then, in addtion, other files:

- *BlaDes.in* (r, twist, chord, attached prfile name),
- *ProThick.in* which maps airfoil names to their (relative) thickness,
  **Important:** This file has to have a header line
- *ThickDis.in* which gives with few entries $r/R_{tip}$ and corresponding t/c,
- *.aer: files with airfoil data $AOA(\alpha), c_L, c_D, c_M$ (not used).

are needed. Most of the input (more or less) should be self-explaining. Lines with 3 numbers a are: first, last and number of values (wind speed and pitch).

Below examples are given,

Fig. (5) and Fig. (4) give an impression of what kind of thickness distribution have been and will be used.

Recently, [24] investigated a 15 MW reference blade in more detail. For reducing the mass from 71to to 63to a considerable change of thickness (see Fig 6) was necessary. This underlines again the importance of this file.

Main output file is *Bem.out*

| | |
|---|---|
| DesMode | .F. |
| BladeNo | 3.0 |
| dens | 1.225 |
| Rhub | 0.3 |
| Rtip | 63.0 |
| windrage | 11.4 11.4 1 |
| rpm | 12.1 |
| Pitchr | 0.0 0.0 1 |
| Nsec | 70 |
| . . . . | |

Table 1: Part of a sample job description file *Machine.in* based on NREL's 5MW reference wind turbine



| r | Twist | chord | Profile Name |
|---|---|---|---|
| 0.0000 | 15.5946 | 5.2000 | CYL1 |
| 2.4000 | 15.5911 | 5.2083 | CYL2 |
| 4.8000 | 15.4288 | 5.2357 | FF50 |
| 7.2000 | 14.9891 | 5.2889 | FF50 |
| 9.6000 | 14.3263 | 5.3606 | FF50 |
| 12.0000 | 13.4947 | 5.4433 | FF50 |
| 15.0000 | 12.3001 | 5.5510 | FF50 |
| 18.0000 | 11.0323 | 5.6501 | FF50 |
| 20.2841 | 10.0834 | 5.7110 | FF36 |
| . . . . | | | |
| 118.7179 | −1.3914 | 1.7239 | FF21 |
| 118.9744 | −1.3628 | 1.6717 | FF21 |
| 119.2308 | −1.3336 | 1.5813 | FF21 |
| 119.4872 | −1.3038 | 1.4157 | FF21 |
| 119.7436 | −1.2734 | 1.1027 | FF21 |
| 120.0000 | −1.2424 | 0.5000 | FF21 |

Table 2: Sample blade description file *BlaDes.in* for NREL/IEAwind 15MW reference wind turbine

| NAME | rel thickness |
|---|---|
| CYL1 | 1.0 |
| CYL2 | 0.95 |
| FF50 | 0.5 |
| FF36 | 0.36 |
| FF33 | 0.33 |
| FF30 | 0.3 |
| FF27 | 0.27 |
| FF24 | 0.24 |
| FF21 | 0.21 |

Table 3: Sample Thickness assigment file *ProThick.in* for NREL/IEAwind 15MW reference wind turbine



| | |
|---|---|
| 0.0000 | 1.0 |
| 0.0200 | 0.98 |
| 0.1500 | 0.500 |
| 0.2452 | 0.360 |
| 0.3288 | 0.330 |
| 0.4392 | 0.301 |
| 0.5377 | 0.270 |
| 0.6382 | 0.241 |
| 0.7717 | 0.211 |
| 1.0000 | 0.211 |

Table 4: Sample Thickness distribution file *ThickDis.in* for NREL/IEAwind 15MW reference wind turbine

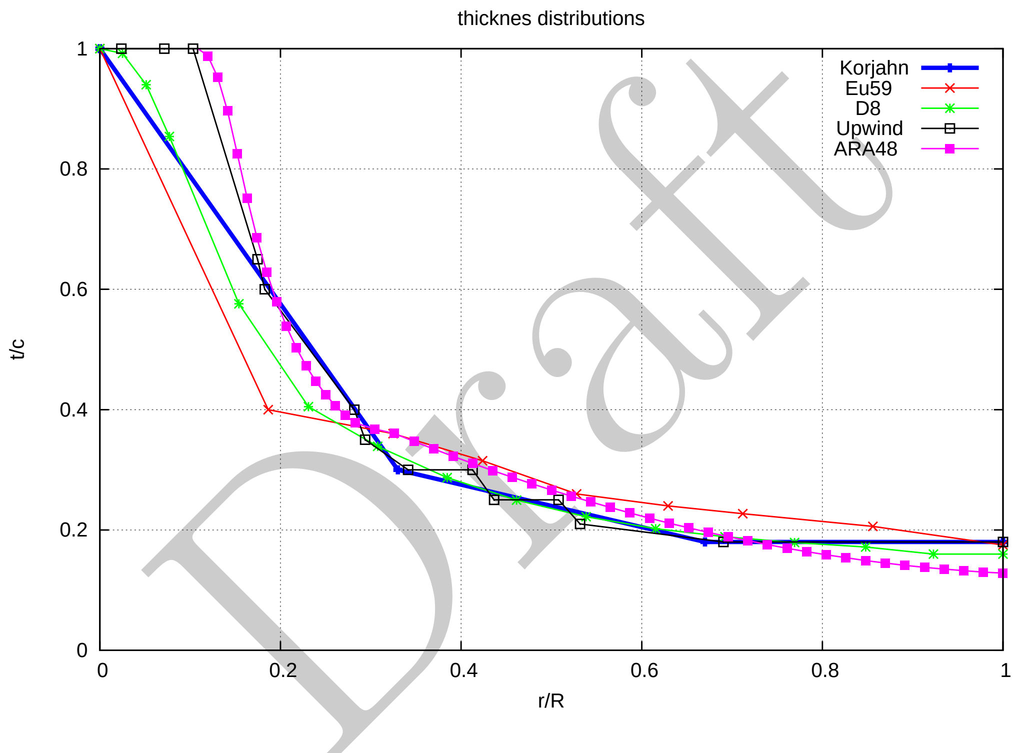


Figure 4: Sample thickness distributions

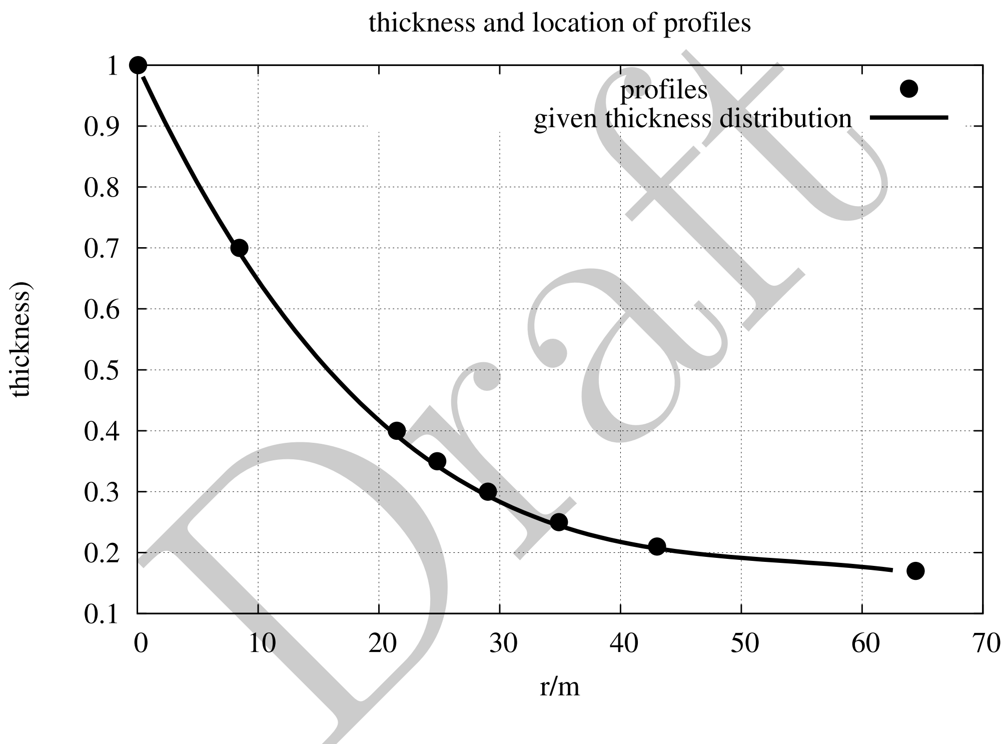


Figure 5: Refined thickness distribution from NREL 5 MW

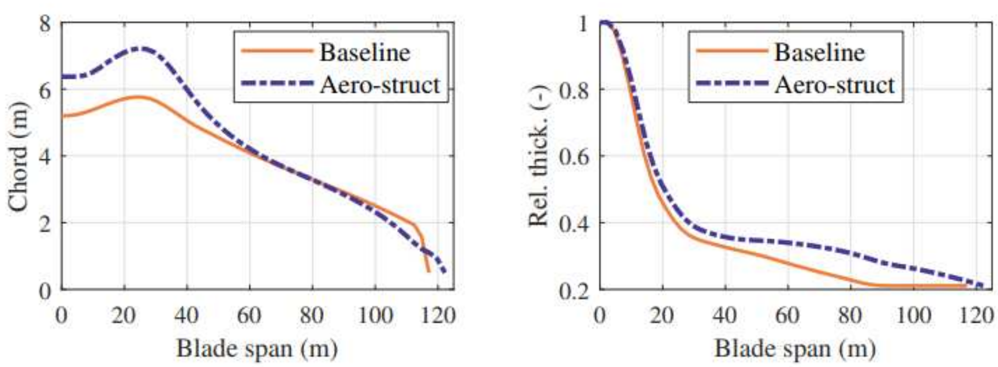


Figure 4: Chord and relative thickness distributions.

Figure 6: Thickness distribution change to decrease mass for a 15 MW reference blade [24]

| r | a | ap | F | w | chord | twist | phi | aoa | cL | cD | L2D | cNo | cTa | dT | dQ | iter | err | th | Prof |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.598 | 0.334 | −0.334 | 1.0 | 6.004 | 5.202 | 15.596 | 87.4 | 71.8 | 0.000 | 0.481 | 0.000 | 0.481 | −0.022 | 0.20 | −0.01 | 3 | 0.0E+00 | 0.99 | CYL2 |
| 1.794 | 0.134 | −0.134 | 1.0 | 7.861 | 5.205 | 15.598 | 82.3 | 66.7 | 0.000 | 0.444 | 0.000 | 0.440 | −0.059 | 0.31 | −0.04 | 3 | 0.0E+00 | 0.98 | CYL2 |
| 2.990 | 0.076 | −0.076 | 1.0 | 8.519 | 5.213 | 15.573 | 77.3 | 61.7 | 0.000 | 0.388 | 0.000 | 0.379 | −0.085 | 0.31 | −0.07 | 3 | −0.2E−06 | 0.97 | CYL2 |
| 4.186 | 0.045 | −0.045 | 1.0 | 9.009 | 5.226 | 15.495 | 72.5 | 57.0 | 0.000 | 0.303 | 0.000 | 0.289 | −0.091 | 0.27 | −0.08 | 3 | −0.2E−06 | 0.95 | CYL2 |
| 5.382 | 0.040 | −0.020 | 1.0 | 9.353 | 5.246 | 15.347 | 67.5 | 52.2 | 0.060 | 0.303 | 0.197 | 0.303 | −0.061 | 0.31 | −0.06 | 4 | −0.1E−04 | 0.92 | FF50 |
| 6.578 | 0.038 | −0.002 | 1.0 | 9.730 | 5.273 | 15.128 | 62.8 | 47.7 | 0.144 | 0.297 | 0.484 | 0.330 | −0.008 | 0.36 | −0.01 | 4 | −0.3E−04 | 0.89 | FF50 |
| 7.774 | 0.040 | 0.011 | 1.0 | 10.149 | 5.305 | 14.848 | 58.4 | 43.5 | 0.245 | 0.283 | 0.864 | 0.370 | 0.060 | 0.44 | 0.07 | 5 | −0.9E−07 | 0.85 | FF50 |
| 8.970 | 0.043 | 0.021 | 1.0 | 10.608 | 5.340 | 14.519 | 54.2 | 39.7 | 0.356 | 0.263 | 1.354 | 0.421 | 0.135 | 0.56 | 0.18 | 6 | 0.0E+00 | 0.81 | FF50 |
| 10.16 | 0.049 | 0.028 | 1.0 | 11.106 | 5.379 | 14.144 | 50.4 | 36.3 | 0.469 | 0.238 | 1.966 | 0.482 | 0.210 | 0.70 | 0.31 | 6 | 0.0E+00 | 0.76 | FF50 |

Table 5: Sample output file *Bem.out* for NREL/IEAwind 15MW reference wind turbine

# 6 Mode: Design

If the design flag is switched on, the lower part of *Machine.in* is important and will be used. As chord from Betz and/or Schmitz usually will give non-zero chord at any sections, a tip-length must be given within its range chord goes down to zero. Two shapes can be chosen:

- Parabolic "P" and
- Elliptic "E".

The last one give a vertical tangent at the tip and the first one is a simple quadratic parabola defined by two points (begin and end (=rtip)) and slope of c(r) at the begin of the tip region.

**Note**: *ImpChord* flag is not used at the moment. Improvement of chord (to proceed to more monotonic-like behavior, see [12] sheet 11) is achieved by smoothing with *Bezier* polynomials.

In addition to Korjahn's $a = 1/3$ approach *DesSchema = 1*, we use *DeSchema = (2,3)* for other Schemas (with very low differences), as described in section 6.1.

## 6.1 Aerodynamic Optimization

### 6.1.1 Betz' and other criteria

We will not give a complete list or discuss in much detail the various interpretations of what an optimization might be and how this may be reached. Only the following three are implemented:

- Betz: $a(r) = 1/3 = const.$,
- Sørensen's (2022), modified *Glauert's* approach[9], see Fig. 7 and
- Joukovskie's: $\Gamma(r) = const.$

(1) Betz: no further explanation needed.

(2) Sørensen [9] argued that close to tip tip $a \to 2/5$, see Fig. 7.

(3) The last one is more subtle; to first order (in a) it is equivalent to Betz', but to 2nd order:

$$a(1-a) = \frac{\lambda B \Gamma (1+a')}{4\pi}\,. \tag{6}$$

To complete, a model for $a'$ has to be added, for example

$$a' = \frac{1-3a}{4a-1} \text{ (Glauert) or} \tag{7}$$

$$a' = \frac{2}{9}\frac{1}{\lambda_r^2} \text{ (Simple approximation)}\,. \tag{8}$$

*DesSchema = 1* refers to Betz' aerodynamic optimized blade $a = 1/3$ for all spans.

| | | | |
|---|---|---|---|
| . | . | . | . |
| 10.00000 | −0.88209 | 0.01386 | −0.04397 |
| −8.00000 | −0.62981 | 0.01075 | −0.05756 |
| −6.00000 | −0.37670 | 0.00882 | −0.06747 |
| −4.00000 | −0.12177 | 0.00702 | −0.07680 |
| −2.00000 | 0.12810 | 0.00663 | −0.08283 |
| −1.00000 | 0.25192 | 0.00664 | −0.08534 |
| 0.00000 | 0.37535 | 0.00670 | −0.08777 |
| 1.00000 | 0.49828 | 0.00681 | −0.09011 |
| 2.00000 | 0.62052 | 0.00698 | −0.09234 |
| 3.00000 | 0.74200 | 0.00720 | −0.09447 |
| 4.00000 | 0.86238 | 0.00751 | −0.09646 |
| 5.00000 | 0.98114 | 0.00796 | −0.09828 |
| 6.00000 | 1.09662 | 0.00872 | −0.09977 |
| 7.00000 | 1.20904 | 0.00968 | −0.10095 |
| 8.00000 | 1.31680 | 0.01097 | −0.10163 |
| 9.00000 | 1.42209 | 0.01227 | −0.10207 |
| . | . | . | . |

Table 6: Sample aerodynamic data *FF21.aer* for NREL/IEAwind 15MW reference wind turbine



| | | |
|---|---|---|
| . . . | | |
| Tiplen | 3.0 | |
| twmax | 20. | |
| chmax | 5.5 | |
| ImpChord | .F. | |
| ImpTwist | .F. | 1 |
| ImpThick | .F. | |
| TwistB | .F. | |
| DesSchema | 2 | |

Table 7: Parameters describing a design case

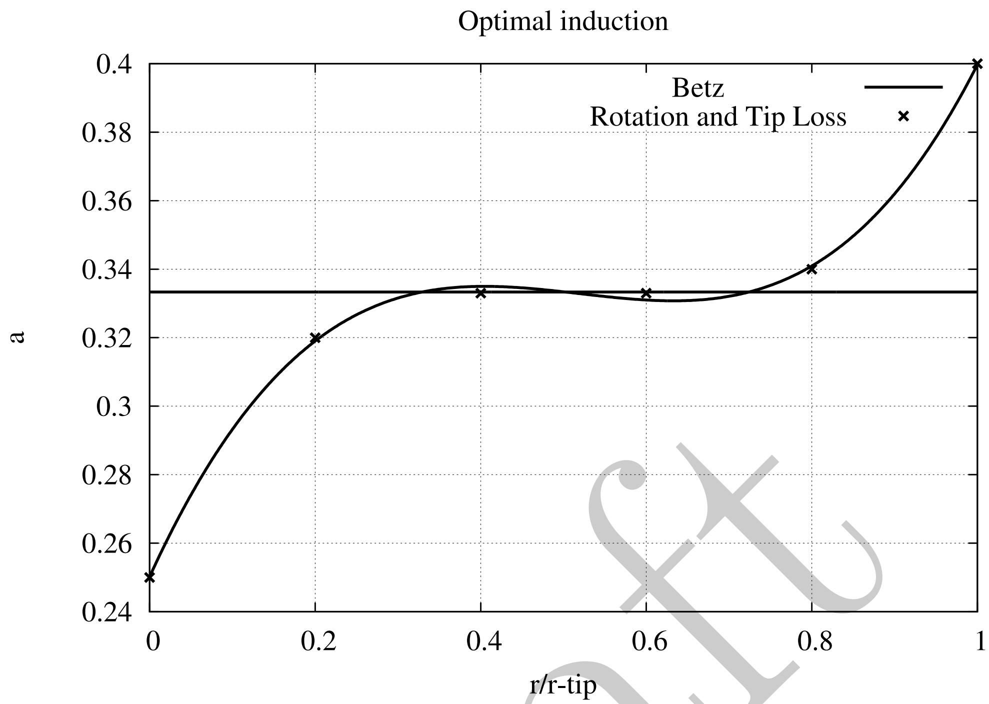


Figure 7: Betz and Sørensen



*DesSchema = 2* refers to Sørensen's different a(r) distribution, [9]. Fig. 7. See [10] for further discussion about aerodynamic optimization and the textbooks in the list of references, esp. [23].

*DesSchema = 3* is implemented but seems not to give any significant changes.

In any case we will only change twist for optimization.

#### 6.1.2 Change of Twist

Our approach to relate twist and $a$ runs via the flow angle and reads as: If $da := a_{opt}(r) - a_{loc} \neq 0$ then locally change twist by

$$d\varphi = -\frac{1}{\lambda_r(1+a')}da \; . \tag{9}$$

#### 6.1.3 Change of Thickness - Arrangement of Profiles

As stated in [12] (sheet 19, first figure) a further means to improve performance is to reduce thickness in the inner part. This is provided in our code by setting the *ImpThick*-bit and providing a changed thickness distribution *ThickDis.new*.

At the very end of *Machin.in* a flag *TwistB* (binary) can be set. It is a very simple way to take *pre-twist* into account. If set to .T. a table of additional twist deformation (along the blade) as function of wind speed has to be given.

# 7 Sample cases

## 7.1 Case 1: The NREL 5MW Baseline blade

As this turbine [11] was also used by Korjahn [12] as a sample case we here report first on output from KSS as well.

Table 8: Rated rotor power of NREL 5MW baseline from various sources. HAWC data from Mr. Hinrichs, aerodyn engineering GmbH, bladed from Mr. Maniok, DNV If all value are equally weighted P = $5356 \pm 89$ kW results

| Source | Value/kW | Deviation (%) |
|---|---|---|
| TP 38060 | 5267 | 0.0 |
| KSS | 5248 | -0.4 |
| FAST | 5293 | 0.5 |
| bladed | 5322 | 1.0 |
| HAWC2 | 5323 | 1.1 |
| q-blade | 5364 | 1.8 |
| Xturb | 5418 | 2.9 |
| WZX | 5478 | 4.0 |
| wt-perf | 5494 | 4.3 |



Except of (out-dated) *wt-perf* (and some other codes) accuracy is within a 1 % range. Difference of KKS to TP38060 is only 0.4 % This may serve as a hint that this BEM-implementation is not totally wrong.

To have a glimpse of the design capability Fig. 8 shows a(r) after 5 loops of twist optimization. *cP* improves from 0.4682 to 0.4685. We agree with [12], sheet 16, that

> For radius < 15m optimum induction is not possible.

In addition, Fig. 9 shows some angles for further assessment.

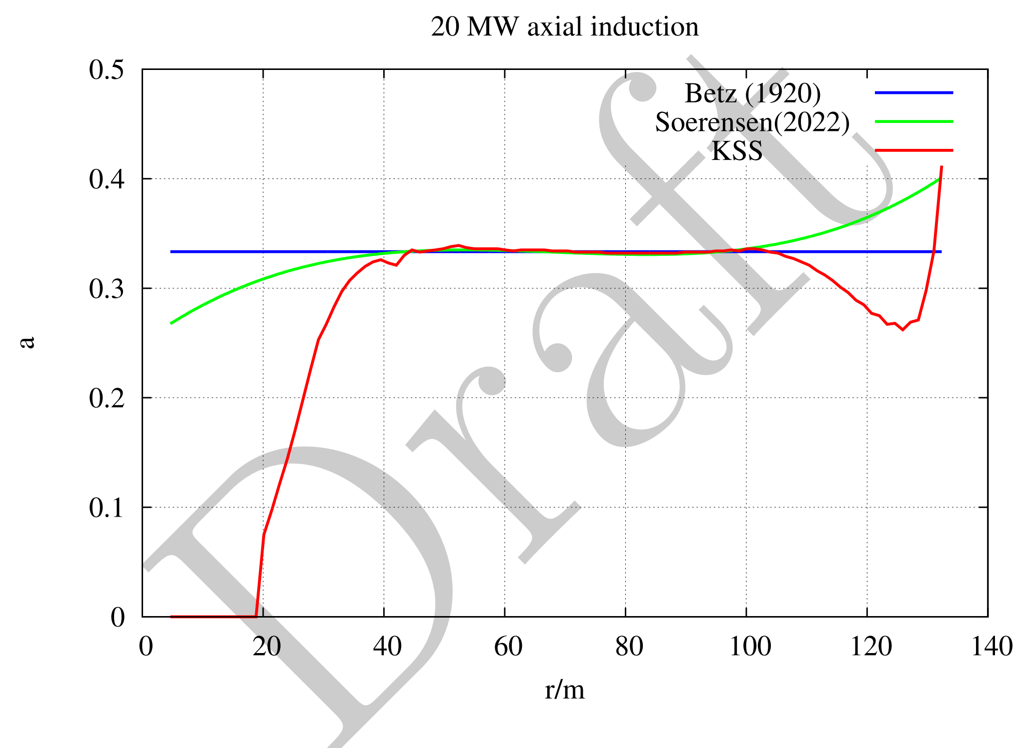


Figure 8: KSS Optimisation after 5 twist loops: a(r)

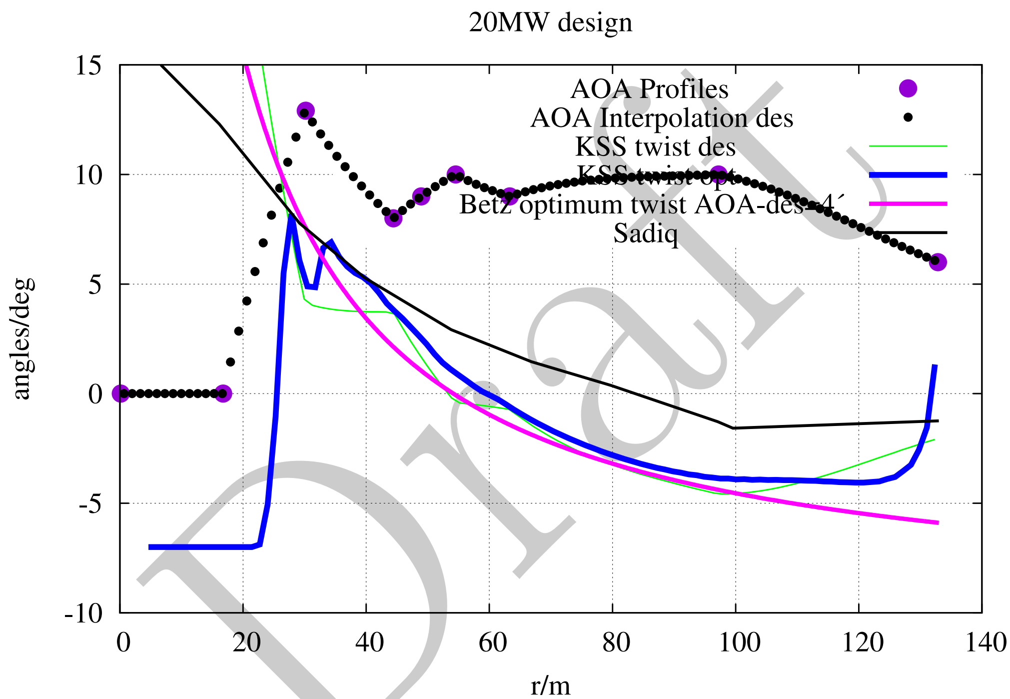


Figure 9: KSS Optimisation (Own 20MW, $r_{tip} = 133m$) after 5 twist loops: some angles

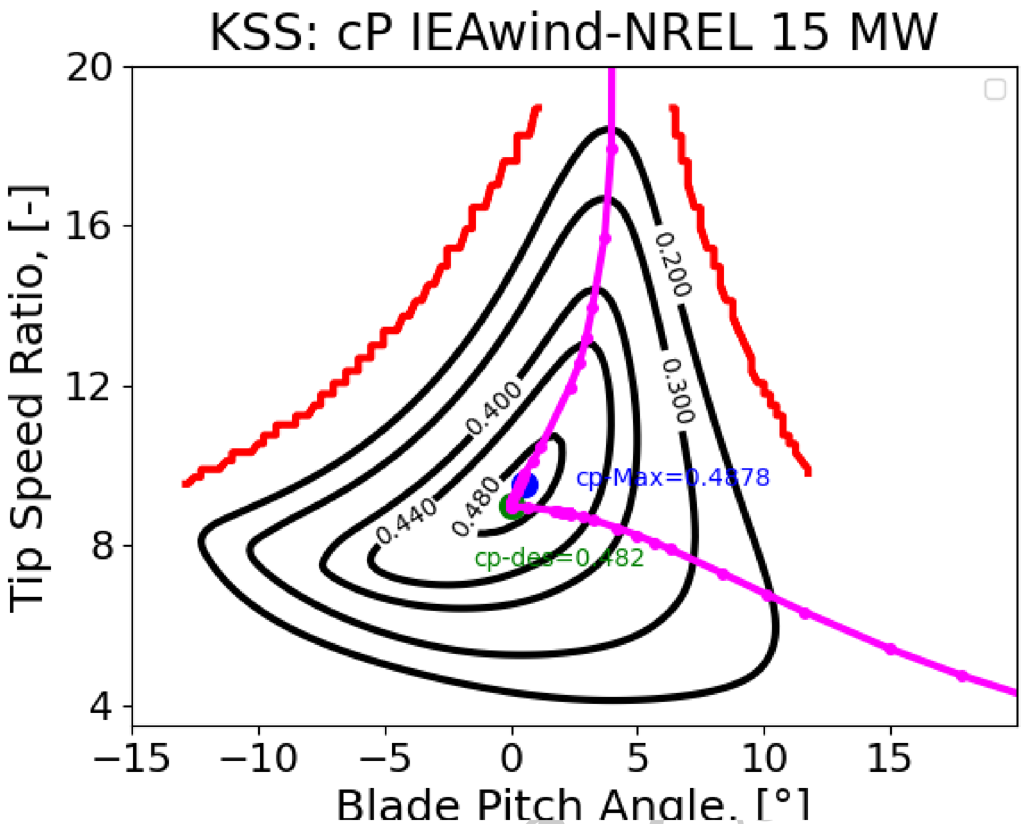


Figure 10: cP map from KSS, including control path (magenta) and an extended pitch variation $-15° < \vartheta < 20°$.

## 7.2 Case 2: A 15MW WT reference blade

The blade described in [4] was also analyzed with KSS, see Figs. 10 and 11. Some difference are visible, but agreement at rated conditions, see table 9 (comparing $c_P$ and $c_T$) are again within 1% range.

Table 9: Comparison for NREL/IEAwind 15 MW reference wind turbine

| Source | $c_P$ | $c_T$ |
|---|---|---|
| TP 76698 | 0.489 | 0.804 |
| KSS | 0.484 | 0.768 |

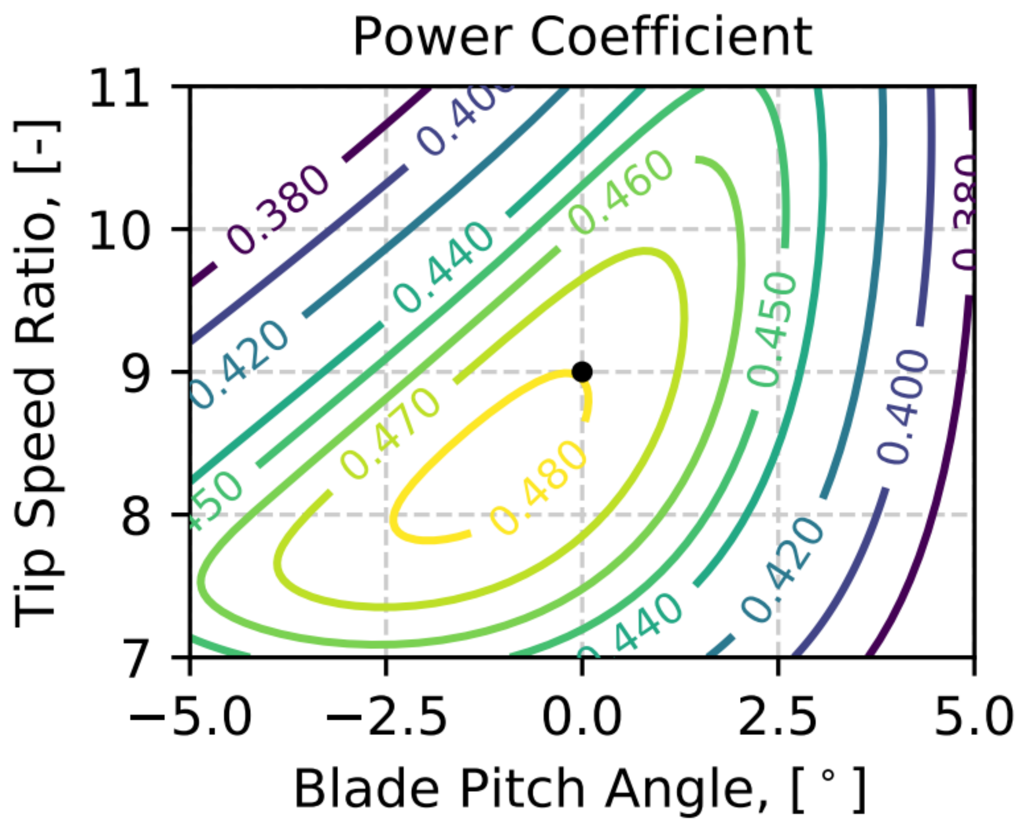


Figure 11: cP map from NREL [4]

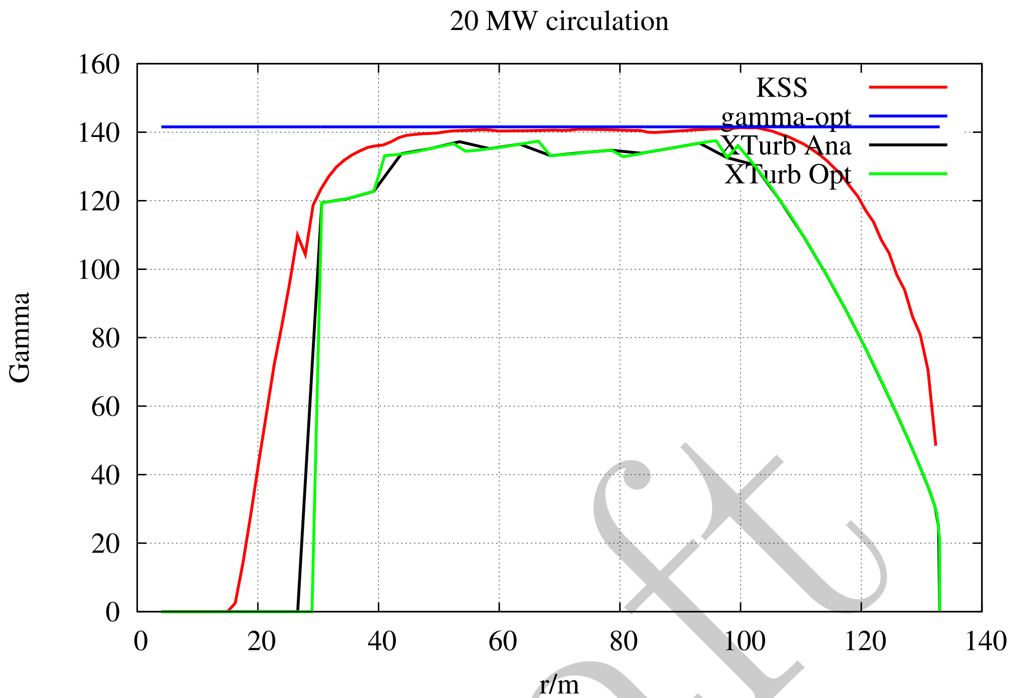


Figure 12: Comparison of circulation for an own 20 MW blade

### 7.3 Case 3: A 20 MW blade

[26] investigated the aerodynamic design of a 20MW blade in more detail. A maximum $cP = 0.4826$ was reached by Betz-mode of optimization after 6 loops and an initial design with $cP = 0.4821$. This is less than 1%. It seems that the restrictions are so strong that noticeable improvement is difficult.

## 8 Comparison with *Xturb*

*Xturb* by Sven Schmitz [23] offers some tools for optimization as well. We compared our 20 MW design [26], see Fig. 12. Unfortunately, XTurb showed an unexpected and non-explainable decrease close to tip ($r/R_{tip} > 0.77$) which makes a reasonable comparison impossible. Nevertheless, the initial design can be improved from $cP_{xT,A} = 0.4299$ to $cP_{xT,D} = 0.4347$ which is about 1.1% higher.

## 9 Summary of investigated blades

Table 10 shows a summary of investigated blades so far:

Table 10: Summary of investigated blades

| Name | Rated Power | Rotor Diameter/m |
|---|---|---:|
| SkyWind NG | 0.6 - 1 kW | 1.5 |
| Baltic Thunder | $\sim$ 1 - 5 kW | 1 |
| Braak | $\sim$ 10 kW | 101 |
| SWT | 1 kW | 1.5 |
| SWT(WINDFLOH) | 14 kW | 10.3 |
| NASA-AMES | 15 kW | 11 |
| E30 | 150 kW | 30 |
| GROWIAN | 1000 kW | 100 |
| NecMicon 80 | 2 MW | 80 |
| MM92 | 2 MW | 92 |
| NREL-Baseline | 5 MW | 126 |
| DTU | 10 MW | 178 |
| CIG10MW | 10 MW | 200 |
| | | 220 |
| NREL | 15 MW | 239 |
| | 17 MW | 248 |
| KUAS20 | 20 MW | 284 |
| 22-RWT | 22 MW | 266 |

# 10 Summary, Discussion and Outlook

Based on the lecture notes from [12] a F90 blade analyze and design tool has been implemented using F90. It was applied and tested to a wide range of WT-blades,see table 10. Agreement with other sources/codes seems to be within a 1% range or smaller seems to be possible.

Findings:

- Choice of thickness distribution and polar data has probably the strongest influence on performance data for a wind turbine blade.
- Improvement (of $c_P$) by the proposed 1-point algorithm seems to be within a 1%-range only.

# 11 Disclaimer

As mentioned earlier, a set of **meaningful** input data has to be provided. There is almost no **consistency** check of input data and this implies that the user has to have some knowledge to avoid crashing of the code and/or meaningless output. Again and again we emphasize:

**Theorem 1.** *You can't calculate what you haven't understood.*

**Theorem 2.** *Only start the calculation, if you know the answer.*

# 12 List of Abbreviations

Table 11: list

| | meaning |
|---|---|
| CIG | Chinese, India, Germany |
| DNV | Det Norske Veritas |
| DTU | (The) Danish Technical University |
| HAWC | Horizontal Axis Wind turbine simulation Code |
| KUAS | Kiel University of Applied Sciences |
| NREL | National renewable Energy Laboratory (USA) |
| SWT | small wind turbine |

# References


[1] C. Bak. Aerodynamic design of wind turbine rotors. page chapter 3, 2013.

[2] T. Burton, N. Jenkins, E. Bossanyi, D. Sharpe, and M. Graham. *Wind Energy Handbook, 3rd. Ed.* John Wiley and Sons, Hoboken, NJ, USA, 2020.

[3] D.C Maniaci. An Investigation of WT-Perf Convergence Issues. In *49th AIAA Aerospace Sciences meeting.*

[4] Gaertner, E. and Rinker, J. and Sethuraman L and Zahle, F. and Anderson, B. and Barter, G. and Abbas, N. and Meng, F. and Bortolotti, P. and Skrzypinksi, W. and Scvott, G. and Feil, R. and Bredmose H. and Dykes, K. and Shileds, M and Alen, Chr. and Vislli, A. Definition of the IEA 15-Megawatt Offshore Reference Wind Turbine. NREL/TP-5000-75698, NREL, March 2020.

[5] H. Glauert, editor. *Airplane Propellers.* Reprint: Stanfort University, CA, USA, 1935.

[6] M. Hansen. *Aerodynamics of Wind Turbines, 3rd. Ed.* Routledge, London, UK, 2015.

[7] J. Ledoux and S. Riffo and J. Salomon. Analysis of the Blade Element Momentum Theory. *SIAM Journal on Applied Mathematics*, (81(6)):2596–2621, 2021.

[8] P. K. Jannert. *gnuplot IN ACTION, 2nd Ed.* Manning Publications, 2016.

[9] J.N. Sørensen. Glauert revisted. In *Proceedings of EAWE conference The Science of Making Torque from the Wind*, June 2022.

[10] J. Johansen, H. A. Madsen, M. Gaunaa, and C. Bak. Design of a wind turbine rotor for maximum aerodynamic efficiency. *WIND ENERGY*, 12:261 – 273, 2009.

[11] J. Jonkman, S. Butterfield, W. Musial, and G. Scott. Definition of a 5-mw reference wind turbine for offshore system development. Technical Report NREL/TP-500-38060, NREL, Golden, Co, USA, 2009.

[12] M. Korjan. Predesign rotor blade (full example). Technical Report unpublished, bewind GmbH, Rendsburg, Germany, 2021.

[13] M. L. Buhl, Jr. A New Empirical Relationship between Thrust Coefficient and Induction Factor for the Turbulent Windmill State. NREL/TP-500-36834, NREL.

[14] NN. https://gcc.gnu.org/fortran/.

[15] NN. de.wikipedia.org/wiki/B{\unhbox\voidb@x\bgroup\let\unhbox\voidb@x\setbox\@tempboxa\hbox{e\global\mathchardef\accent@spacefactor\spacefactor}\accent18e\egroup\spacefactor\accent@spacefactor}zierkurve.

[16] NN. www.gnuplot.info.

[17] O. de Vries. Fluid Dynamic Aspects of Wind Energy Conversion. Technical report, AGARDograph Bo. 242, 1979.

[18] W. Press, A. Teukolsky, W. Vetterling, and B. Flannery. *NUMERICAL RECIPES in Fortran, 2nd Ed. The Art of Scientific Computing*. Cambridge University Press, Cambridge, UK, 1992.

[19] Ramdin, S.F. Prandtl tip loss factor assessed. Master's thesis, Delft University of Technology, 2017.

[20] R.E. Wilson and P.B.S Lissaman and S.N. Walker. Aerodynamic Performance of Wind Turbines. Technical report, Oregon State University, 1976.

[21] S.A. Ning. A simple solution method for the blade element momentum equations with guaranteed convergence. *Wind Energgy*, (17):1327–1345, 2014.

[22] Schaffarczyk, A.P. *Introduction to Wind Turbine Aerodynamics, 3rd Ed.* SpringerNature, Berlin, 2024.

[23] S. Schmitz. *Aerodynamics of Wind Turbines*. Wiley, 2020.

[24] Scott, Samuel and Greaves, Peter and Macquart, Terence and Pirrera, Alberto. Comparison of blade optimization strategies for the IEA 15 MW reference wind turbine. In *Proceedings of EAWE conference The Science of Making Torque from the Wind*, June 2022.

[25] J. N. Sørensen. *General Momentum Theory for Horizintal Axis Wind Turbines*. Springer International Publishing Switzerland, 2016.

[26] Syed, S. Aerodynamic Design of a 20MW blade. Master's thesis, Kiel University of Applied Sciences, 2022.