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Steady State Comparisons HAWC2 v12.2 vs HAWCStab2 v2.12

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Publication date:
2016

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Verelst, D. R., Hansen, M. H., & Pirrung, G. (2016). Steady State Comparisons HAWC2 v12.2 vs HAWCStab2 v2.12. DTU Wind Energy. (DTU Wind Energy E, Vol. 0122).

Steady State Comparisons HAWC2 v12.2 vs HAWCStab2 v2.12

Integrated and distributed aerodynamic performance

DTU Wind Energy E-report

$$P = \frac{1}{2} \rho A v^3 C_p$$

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Report number: DTU Wind Energy E-0122
ISBN: 978-87-93278-81-3

Compiled on Tuesday 19th April, 2016 at 16:23

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Department of Wind Energy

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1 Introduction

This reports presents comparison of the steady state HAWC2 [1] [2] [3] simulation results and the HAWCStab2 computations of the DTU10MW reference turbine [4] [5]. It serves as a simple validation for the HAWCStab2 [6] [7] [8] steady state computations. Due to HAWCStab2 the following simplifications are made:

- no gravity
- shaft tilt angle is set to zero since HAWCStab2 assumes the inflow is perpendicular to the rotor plane
- aligned inflow conditions (no turbulence, shear, veer or yaw)
- tower and shaft flexibility are not considered to assure the shaft remains perfectly aligned with the wind inflow vector (horizontal)
- the dynamic stall model is disabled

Further, the HAWC2 model needs to contain as many bodies as there are structural nodes for both structural models to behave in the same way.

There are three test cases considered in the comparison:

- Case 1: no blade flexibility, and the aerodynamic modelling reduced to strip theory: no induction and no tip correction, labelled as "no induction" or "without induction"
- Case 2: no blade flexibility in conjunction with BEM induction model and Prandtl tip correction (labelled as "induction+tip")
- Case 3: flexible blades in conjunction with "induction+tip"
- Case 4: flexible blades and with BEM calculated induction, but without the Prandtl tip correction model, labelled as: "induction only"

Both HAWC2 and HAWCStab2 have the ability to use different aerodynamic models. For the "induction+tip" model, the rotor induced velocities are calculated with Blade Element Momentum theory, and the presence of the tip vortex is accounted for by the Prandtl tip loss model. Although available in both codes, dynamic stall is not included within the scope of this comparison.

By considering these three model variations, potential differences in the results can be more easily related to the different models used in both codes.

This investigation has been carried out with HAWC2 version 12.2 and HAWCStab2 version 2.12.

2 DTU10MW: Comparing Steady State Results

The DTU 10MW reference wind turbine is used for this investigation, and the HAWC2 and HAWCStab2 models for this turbine are available from [5].

This comparison considers the following integrated rotor performance parameters, as function of wind speed:

- Mechanical rotor power
- Rotor thrust

The following distributed blade performance parameters are considered:

- The z-coordinate of the blade section (in blade coordinates) on the x-axis
- Lift and drag coefficients (Cl and Cd respectively)
- Angle of attack (AoA)
- Relative velocity as seen from the blade section (vrel)
- Distributed lateral and axial forces (F_x and F_y respectively) in rotor polar coordinates
- Axial and tangential induced velocities (ax_ind_vel and tan_ind_vel)

2.1 Case 1: Stiff Blades and "no Induction"

This is the most basic and simple comparison possible: an entirely stiff structure, steady and uniform inflow conditions, and basic strip theory for the aerodynamics (no induction, not tip correction, no dynamic stall). From the power curve given in Figure 1 it can be noted that in the absence of deflections, and without the proper aerodynamic model, the nominal power is significantly over estimated.

From Figure 1 is noted that the difference between HAWC2 and HAWCStab2 is very small:

- maximum difference on power output is 60 kW (roughly 0.3% at ≈ 17 MW)
- maximum difference on thrust is 1 kN (roughly 0.1% at 800 kN)

These differences are considered very small and are argued to be caused by the small differences in numerical integration schemes used for integrating the rotor forces.

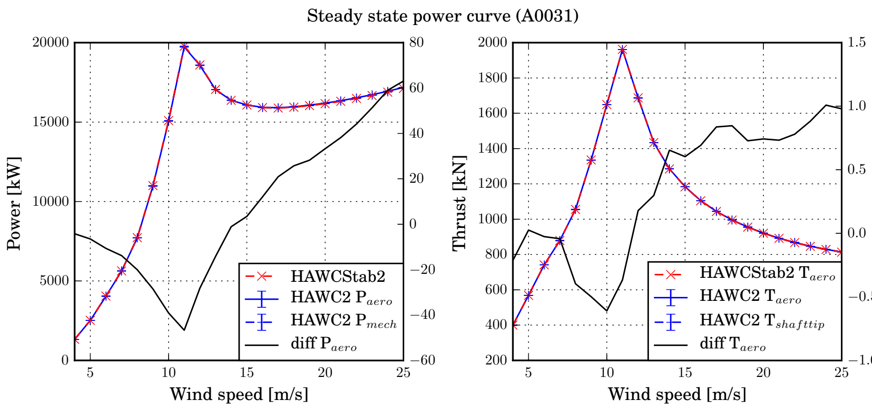

Figure 1: Power and thrust curves. The absolute difference between HAWC2 and HAWCStab2 is labelled as *diff*, and its axis is on the right side of the plot.

Figures 2 to 5 consider the blade distributed aerodynamic parameters. For the fully stiff case with simple aerodynamics the distributed forces compare very well between HAWC2 and HAWCStab2. The minor differences that occur are mainly located within the inner part of the blade. Notice that the induced velocities are zero since the induction model is switched off.

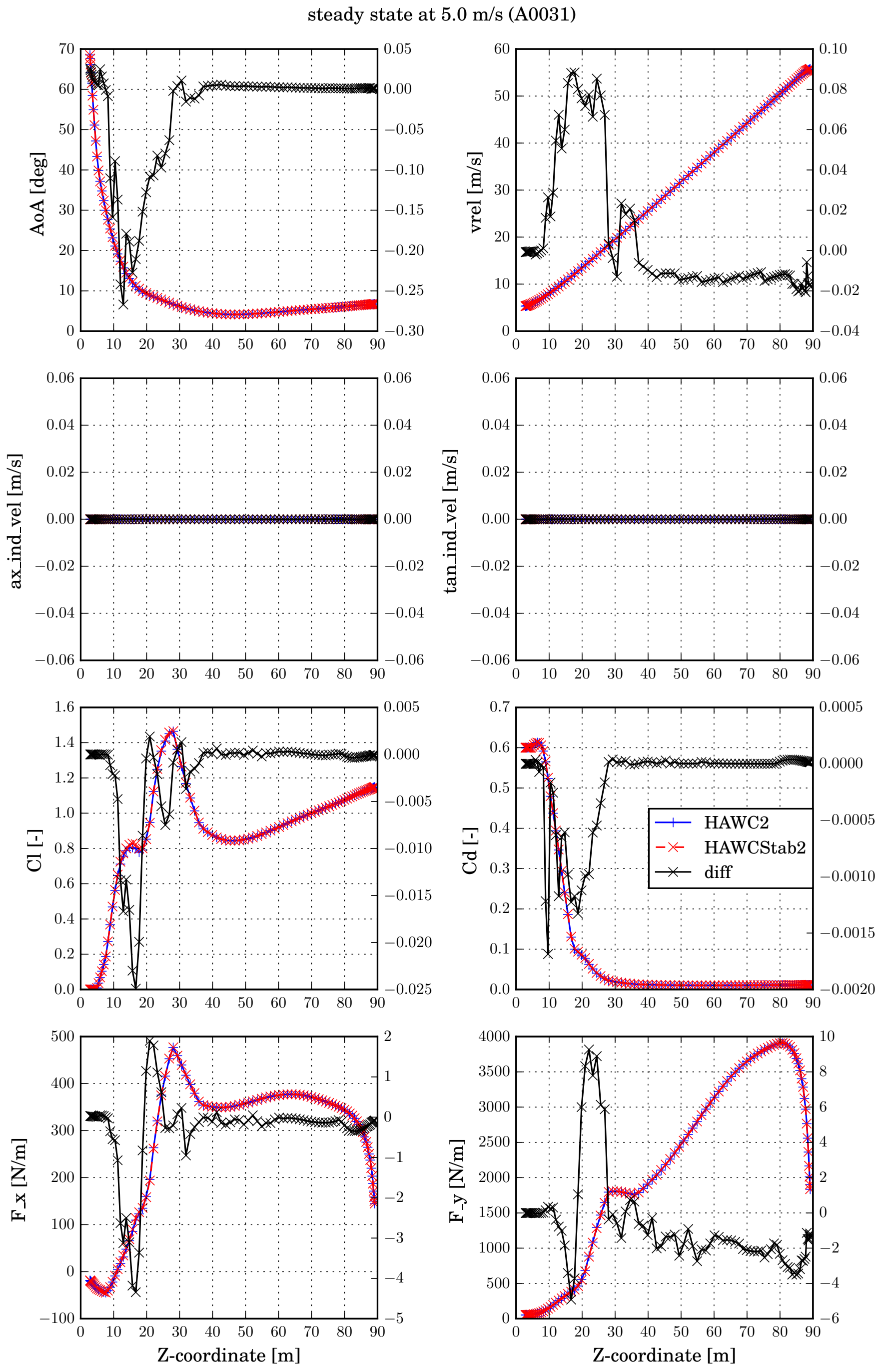

Figure 2: Blade load distribution at 5 m/s. The absolute difference between HAWC2 and HAWCStab2 is labelled as *diff*, and its axis is on the right side of the plot.

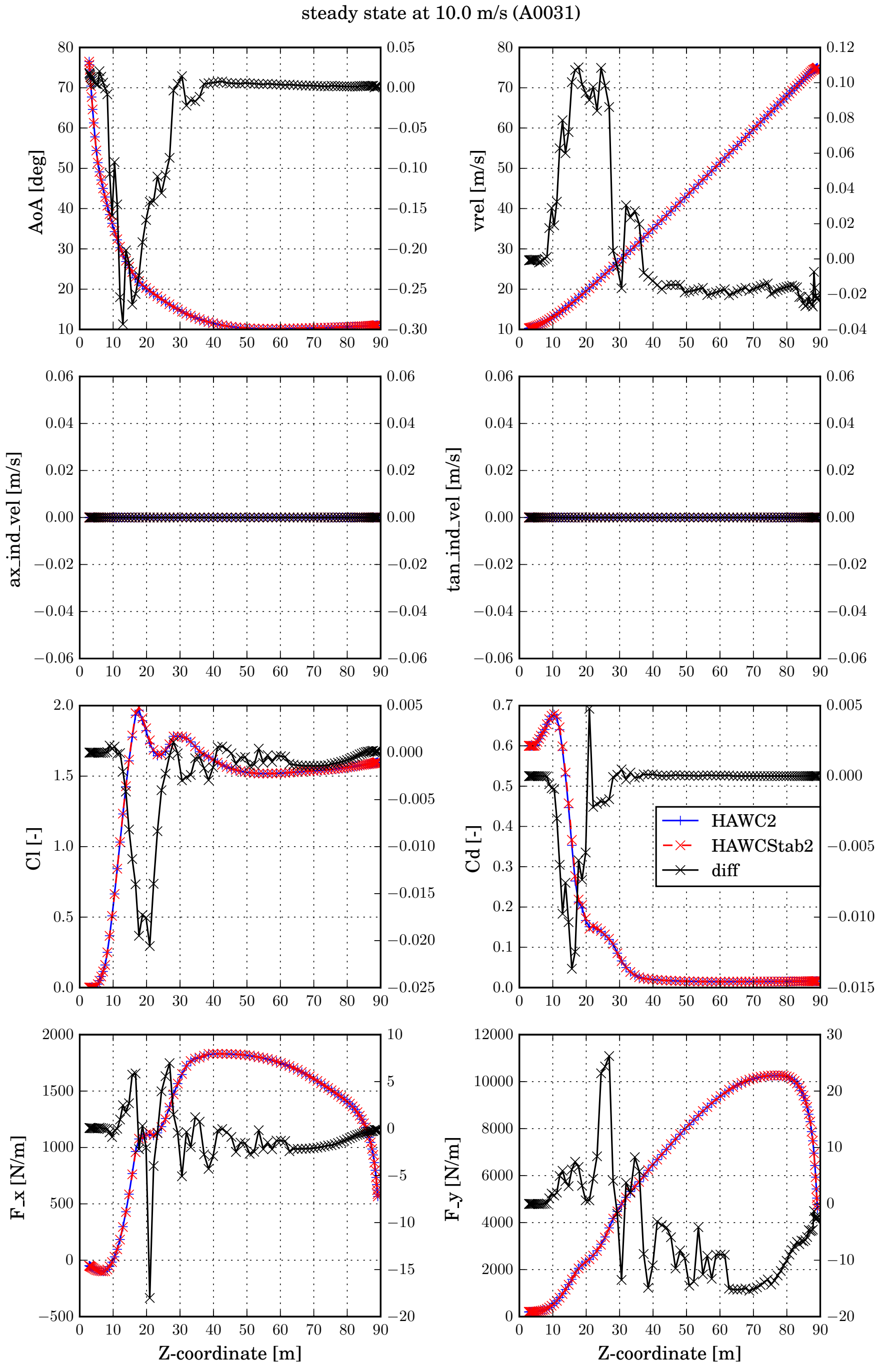

Figure 3: Blade load distribution at 10 m/s

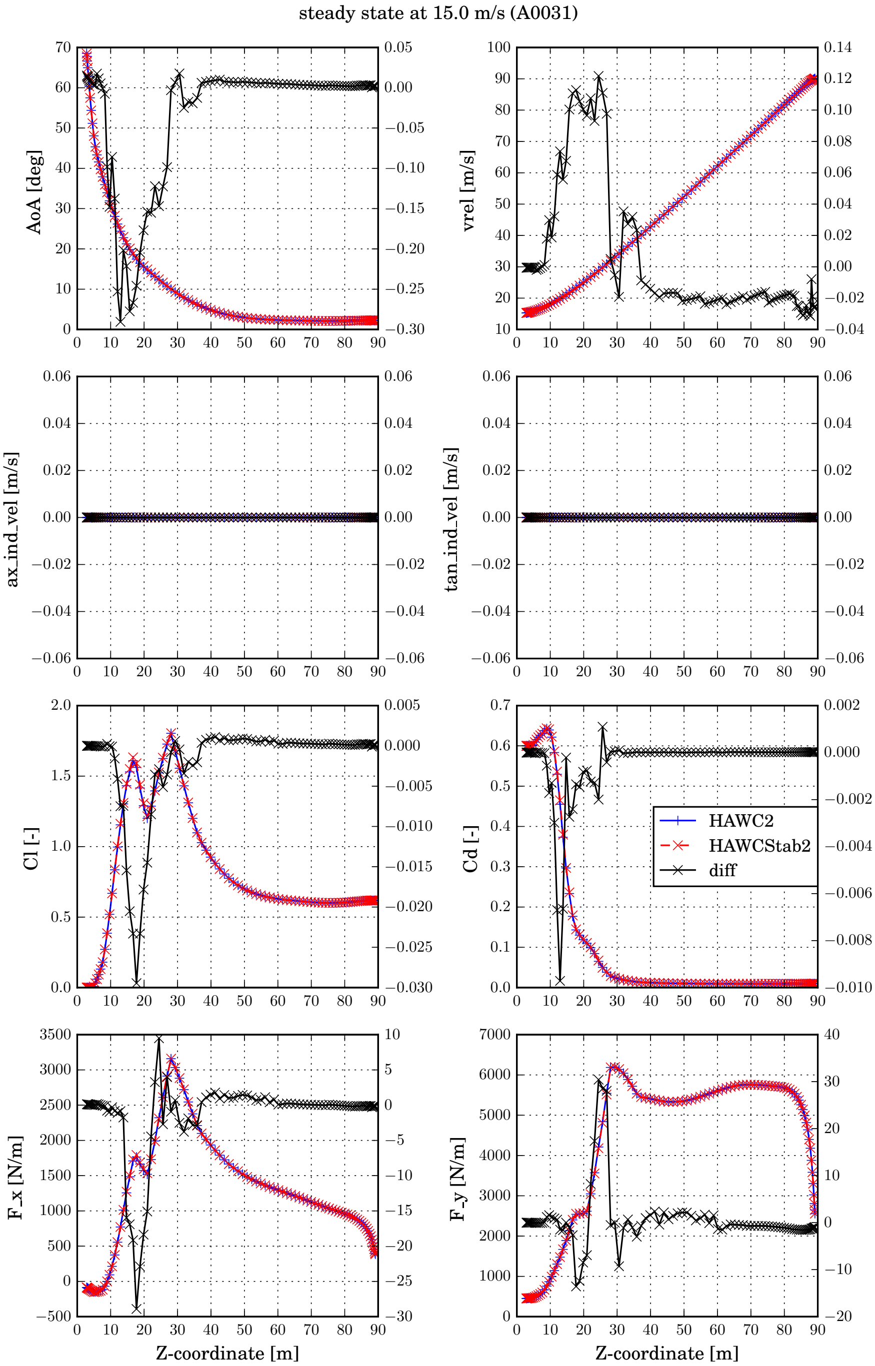

Figure 4: Blade load distribution at 15 m/s

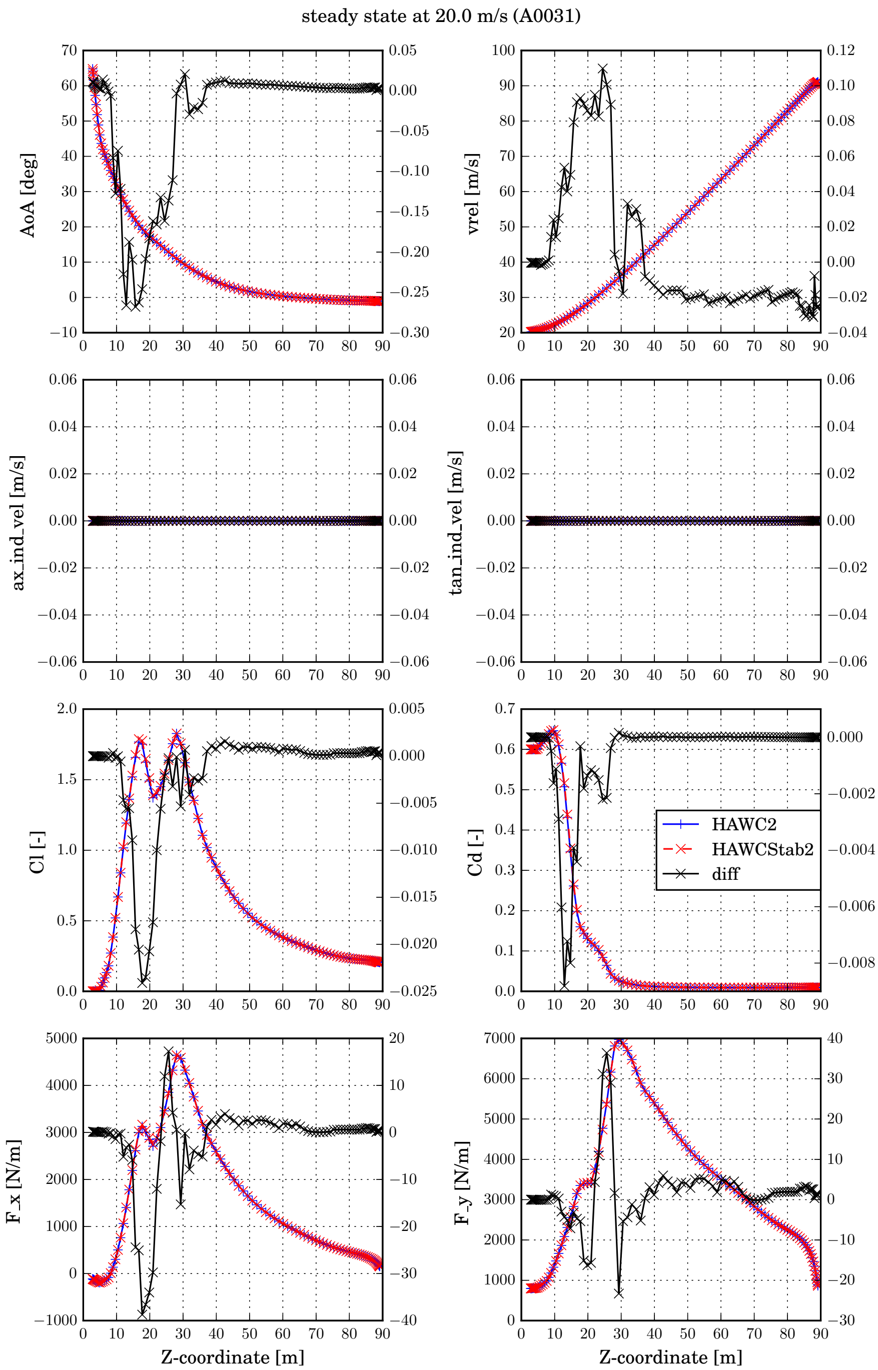

Figure 5: Blade load distribution at 20 m/s

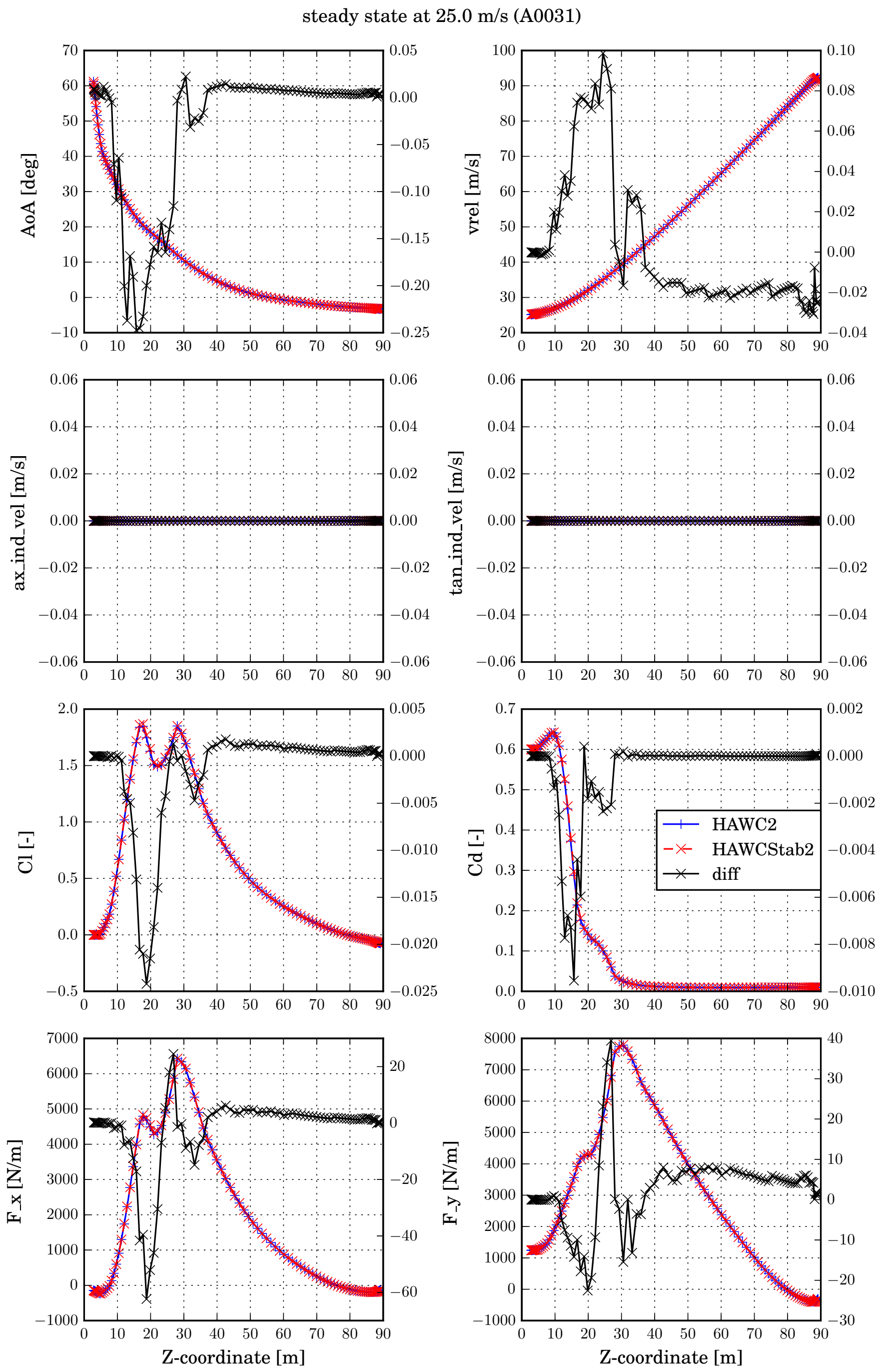

Figure 6: Blade load distribution at 25 m/s

2.2 Case 2: Stiff Blades and "Induction+Tip"

When using a more realistic aerodynamic model, but still stiff blades, the good agreement between HAWC2 and HAWCStab2 still holds. The integrated forces are shown in Figure 7 in the form of the power and thrust curves as function of wind speed. The error between HAWC2 and HAWCStab2 remains well below 1%.

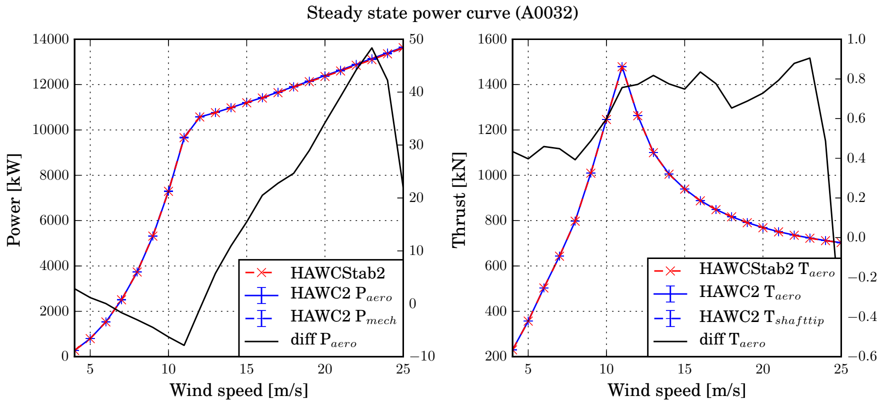

Figure 7: Power and thrust curves. The absolute difference between HAWC2 and HAWCStab2 is labelled as *diff*, and its axis is on the right side of the plot.

The distributed aerodynamic parameters (Figures 8 to 12) show a very good agreement between both codes. However, following minor differences are observed:

- The same minor differences are occurring at the inner part of the blade compared to case 1.
- At the tip a small discrepancy exists due to presence of the tip loss model. A more detailed assessment as of why the tip loss model causes this difference is referred to future work.
- At 25 m/s (see Figure 12) the outboard region (from z-coordinate 70 m and outwards) has negative induced velocities, and in this region the HAWCStab2 results slightly diverge from the HAWC2 steady state results. See section 2.4 for a more detailed discussion.

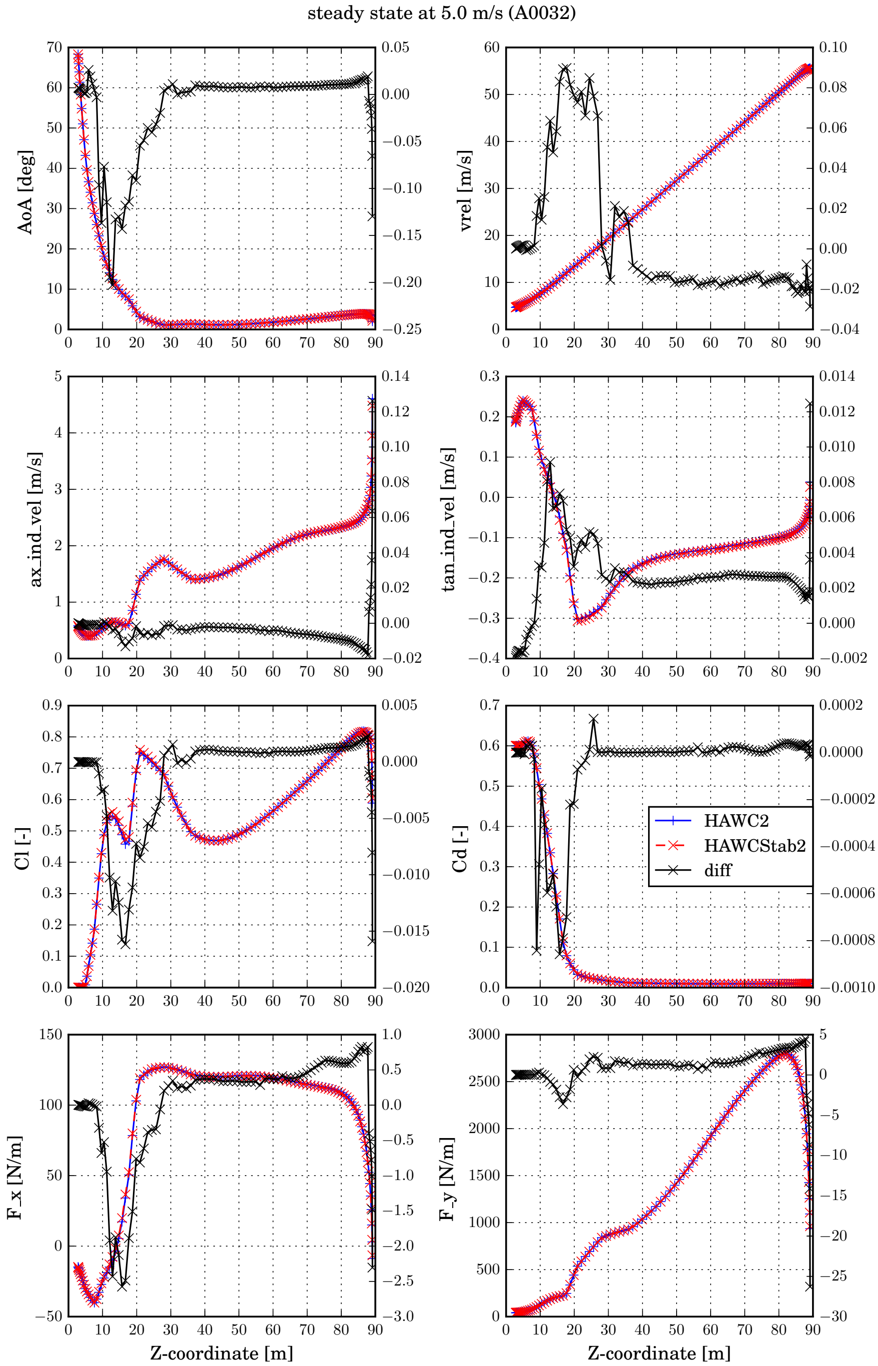

Figure 8: Blade load distribution at 5 m/s

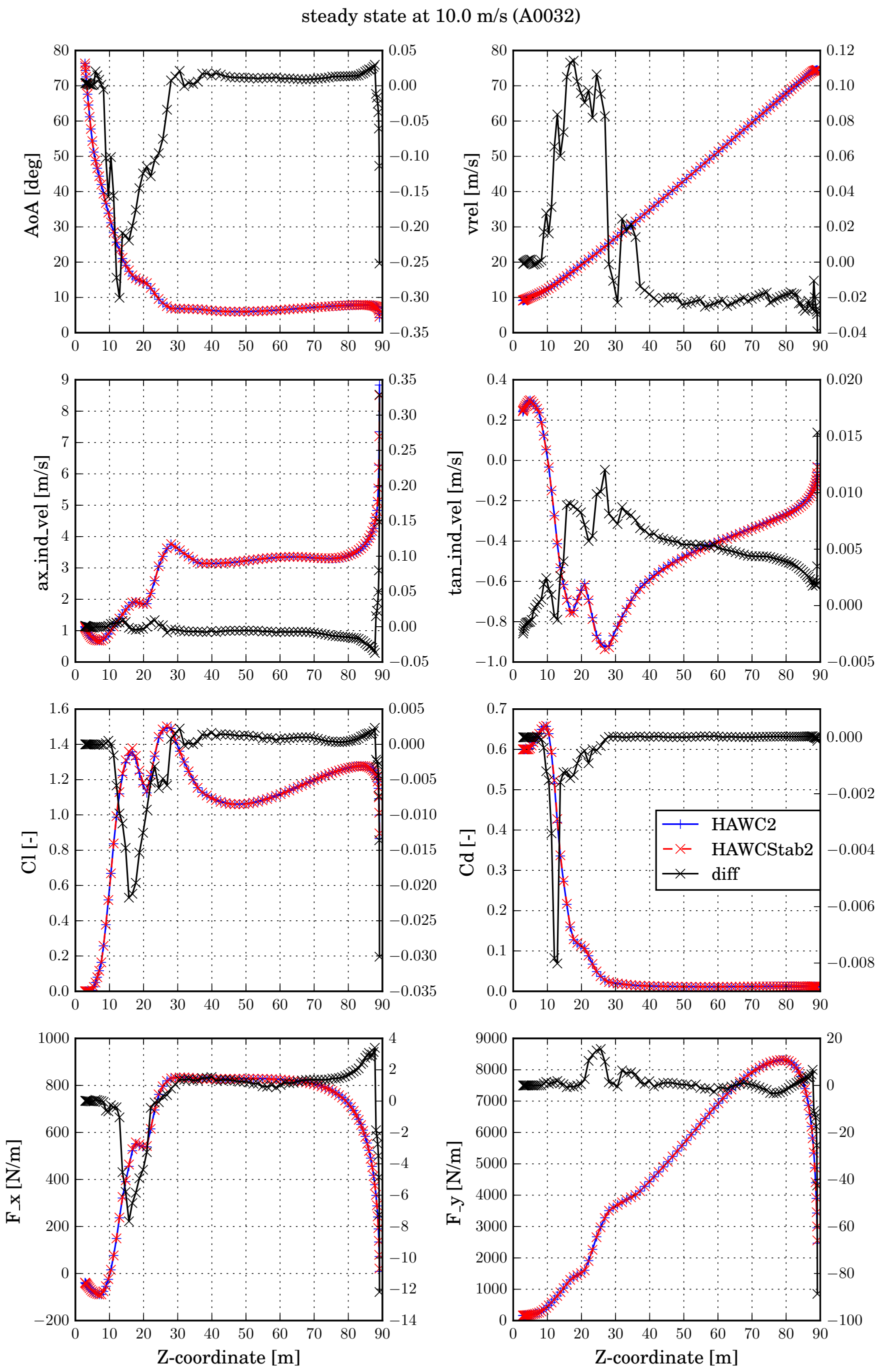

Figure 9: Blade load distribution at 10 m/s

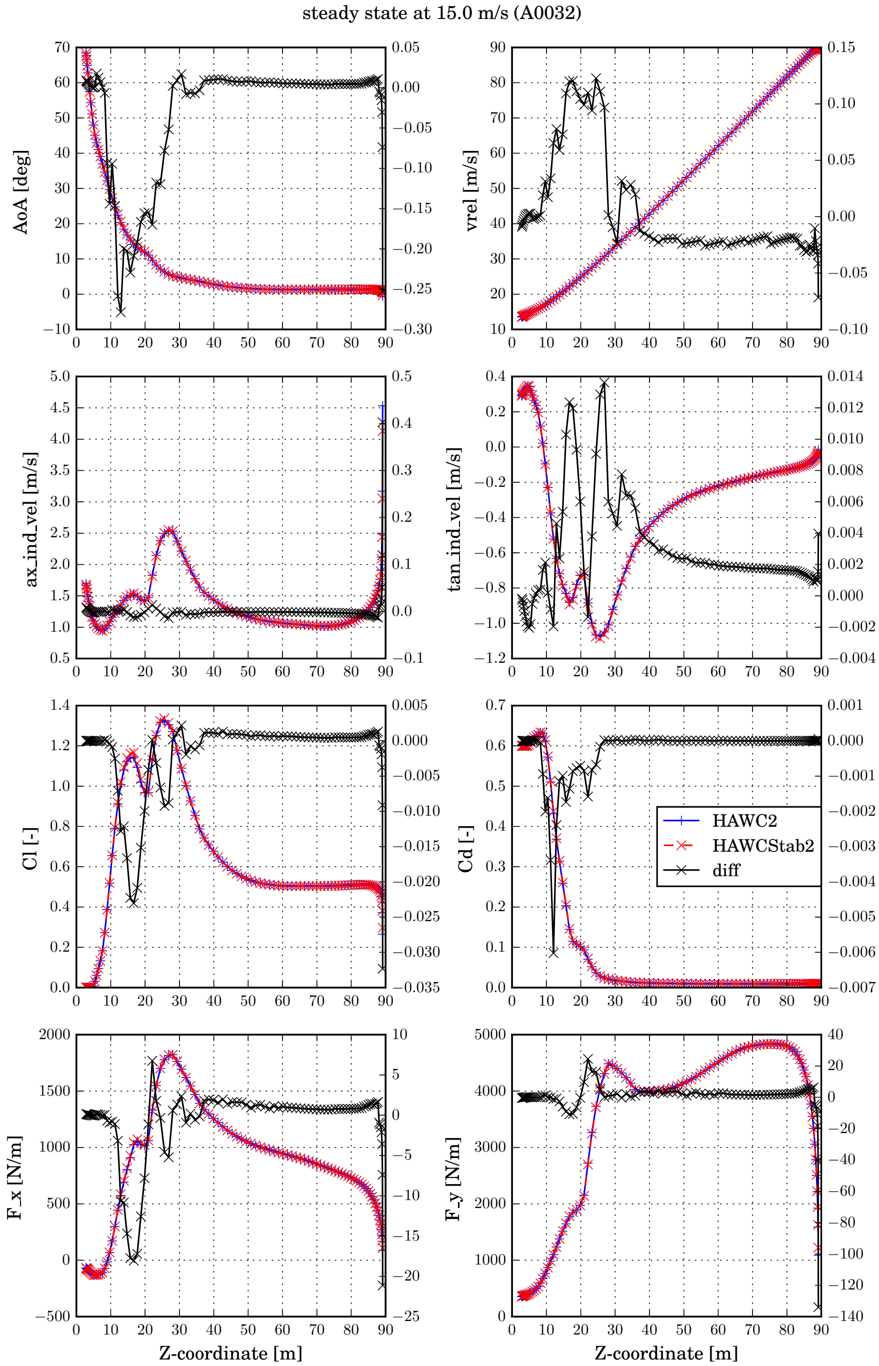

Figure 10: Blade load distribution at 15 m/s

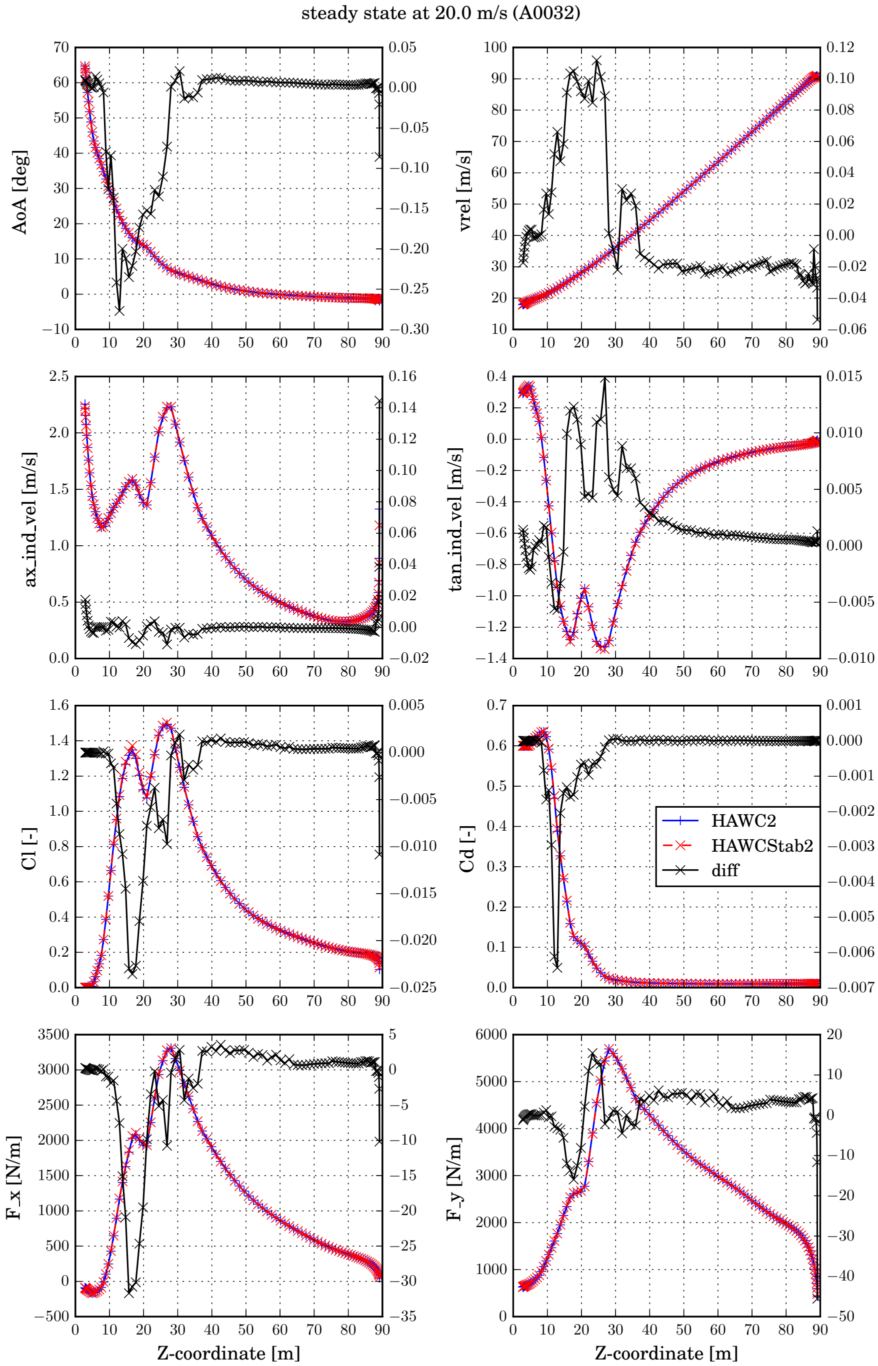

Figure 11: Blade load distribution at 20 m/s

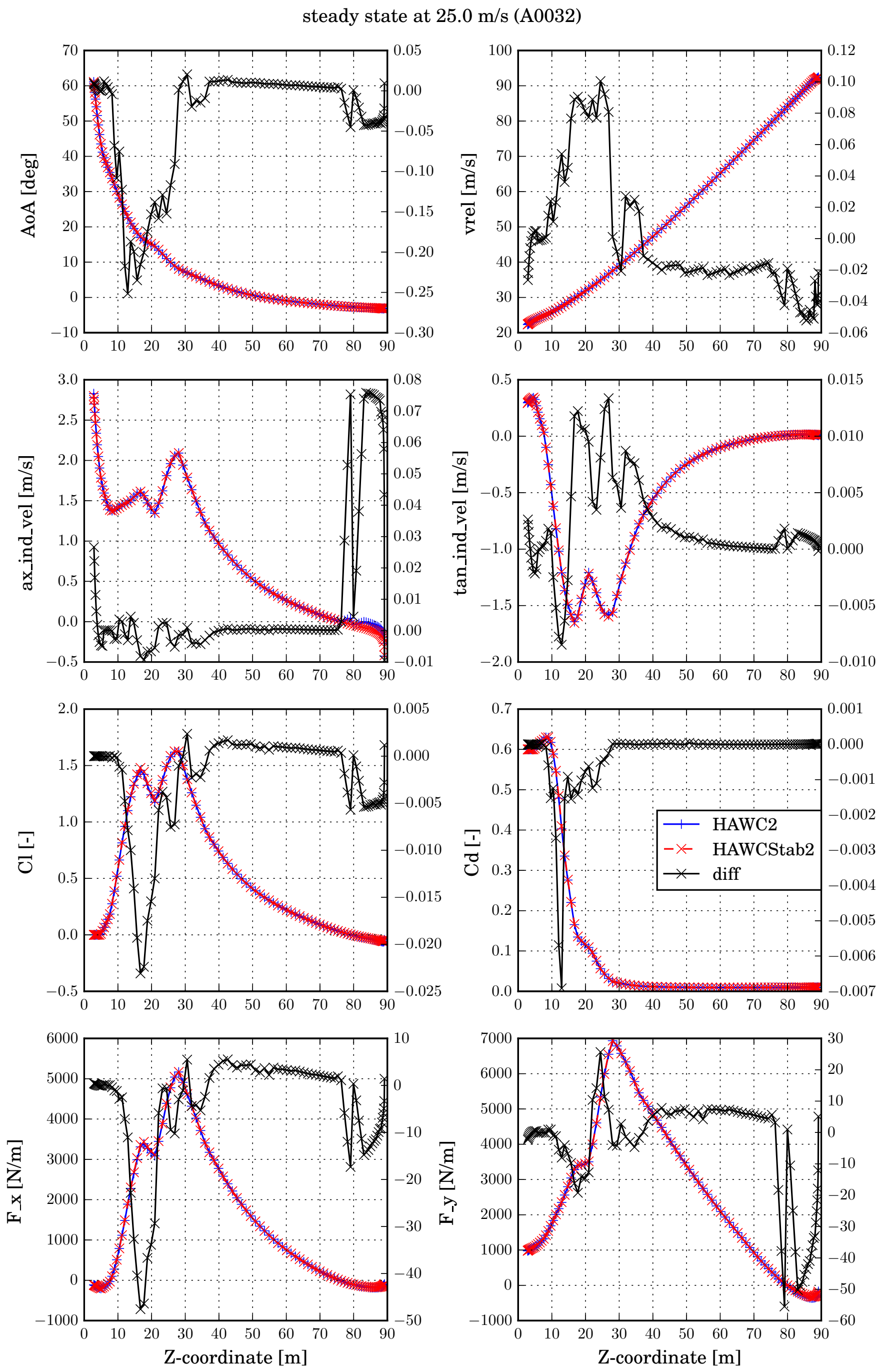

Figure 12: Blade load distribution at 25 m/s

2.3 Case 3: Flexible Blades and "Induction+Tip"

When considering both the "BEM+tip aerodynamic" model and blade flexibility the same consistent and good agreement between both HAWC2 and HAWCStab2 is found. This for both integrated rotor forces (see Figure 13 and distributed aerodynamic parameters (Figures 14 to 17).

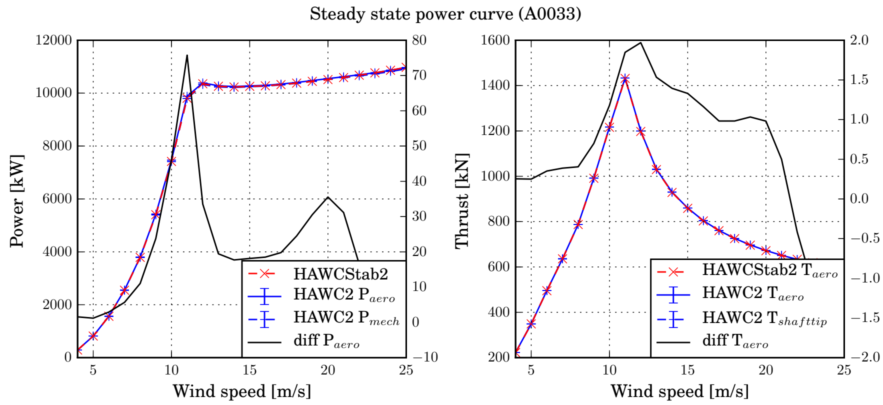

Figure 13: Power and thrust curves. The absolute difference between HAWC2 and HAWCStab2 is labelled as *diff*, and its axis is on the right side of the plot.

The load distributions show similar trends compared to the stiff rotor (case 2, Figures 8 to 12). Without considering the detailed comparison of the blade deflection curves in this report (see section 4), it seems that differences caused by the aerodynamics are minor, and they do not affect significantly the blade deformation.

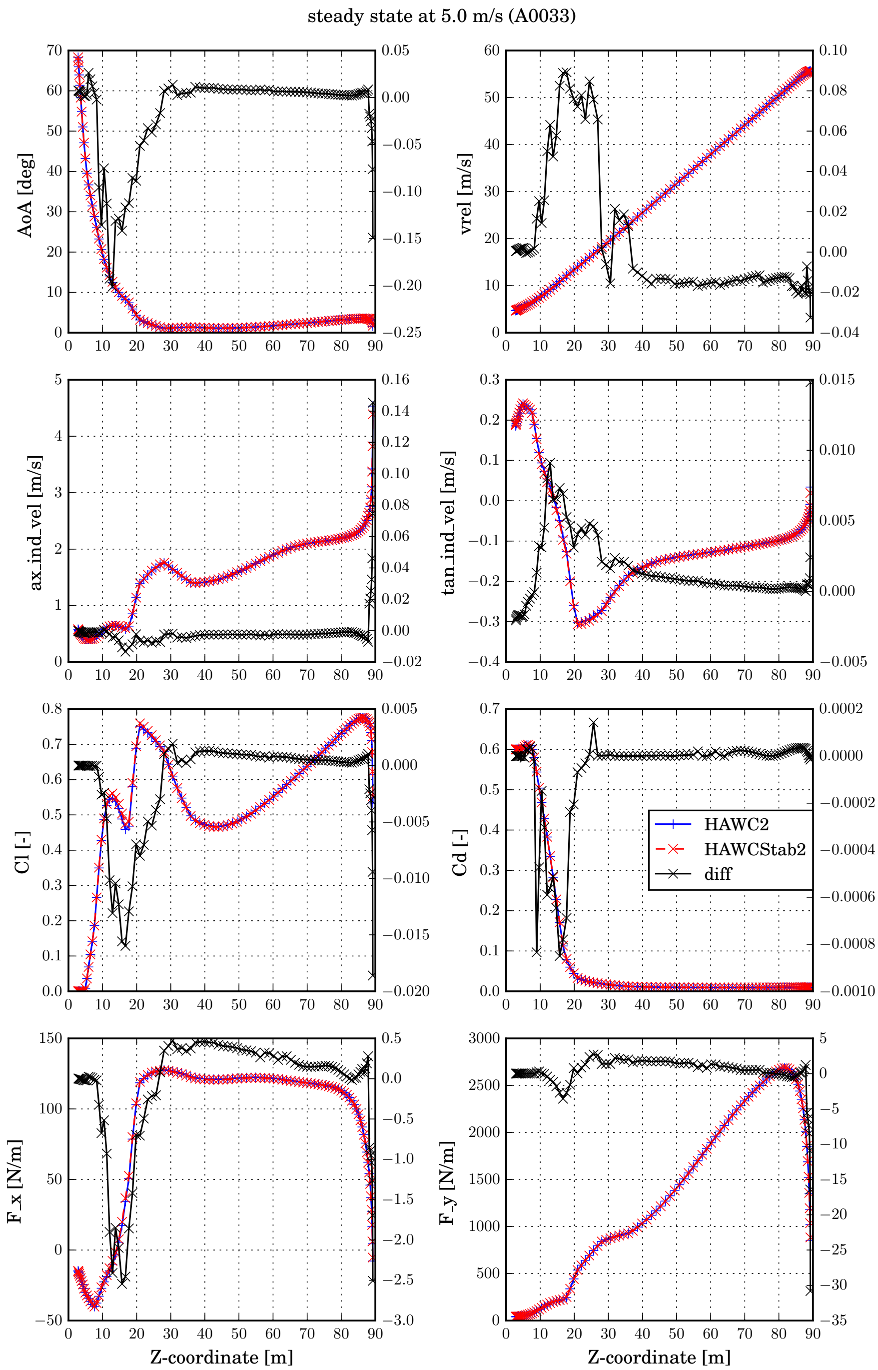

Figure 14: Blade load distribution at 5 m/s

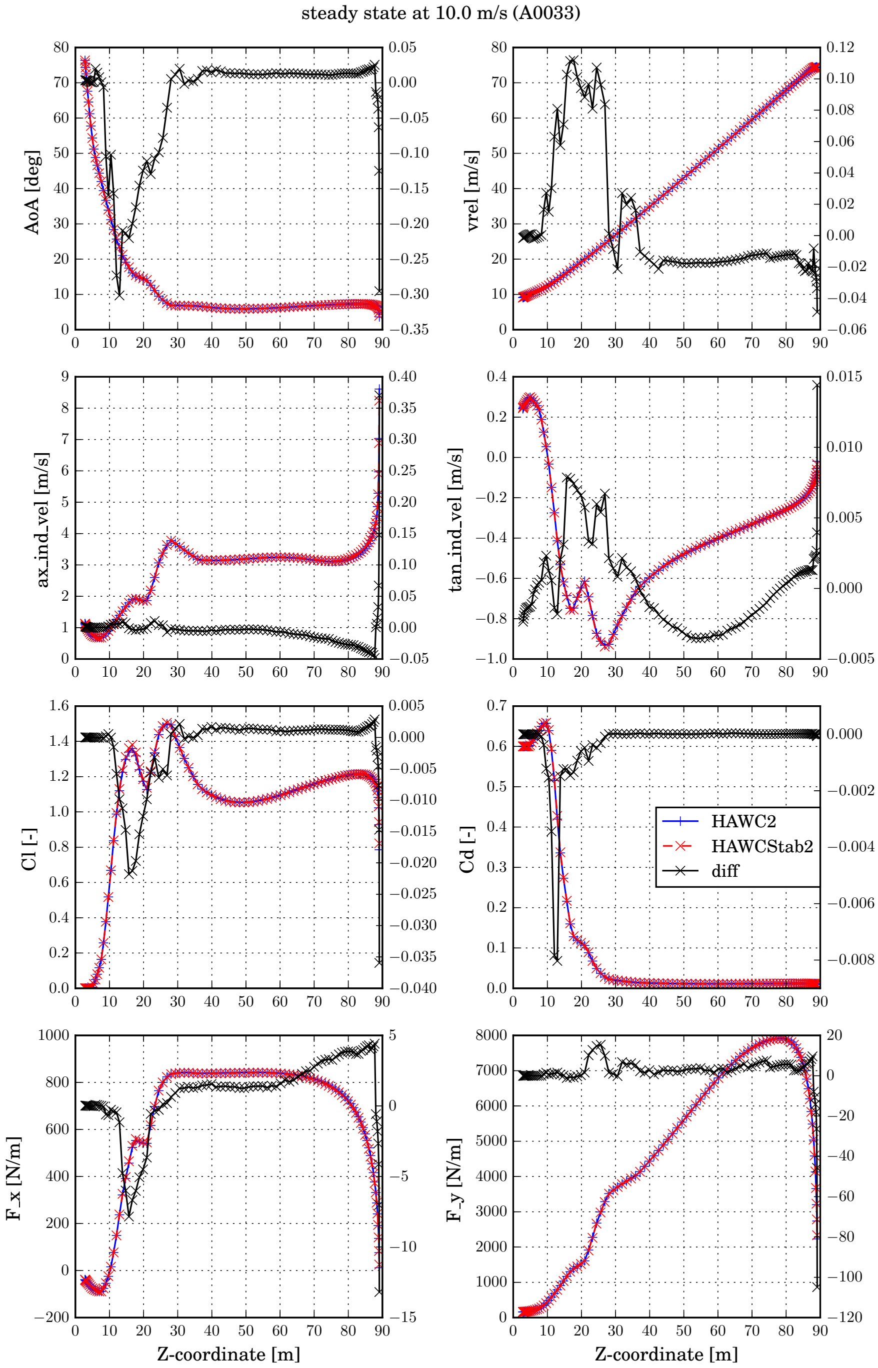

Figure 15: Blade load distribution at 10 m/s

steady state at 15.0 m/s (A0033)

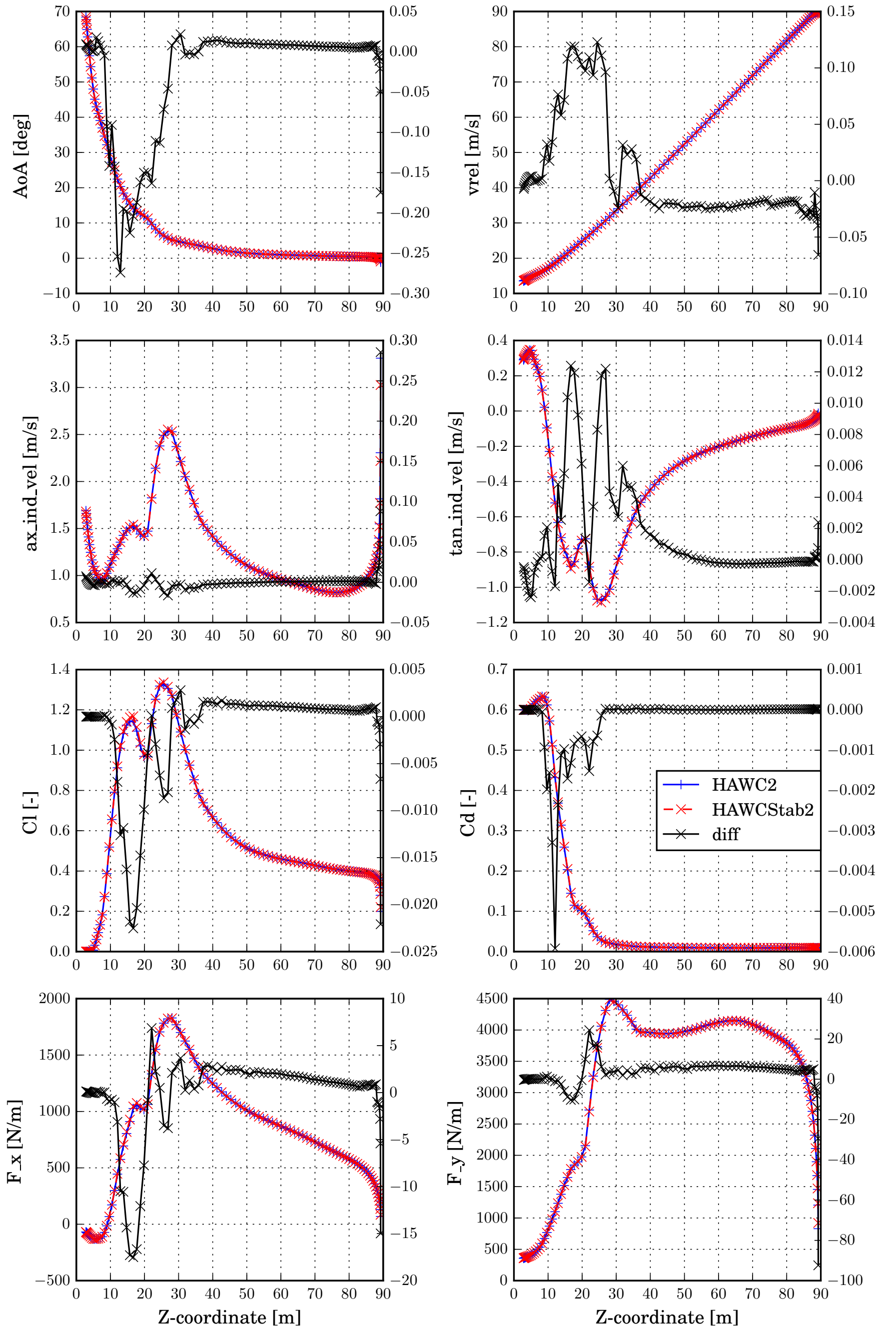

Figure 16: Blade load distribution at 15 m/s

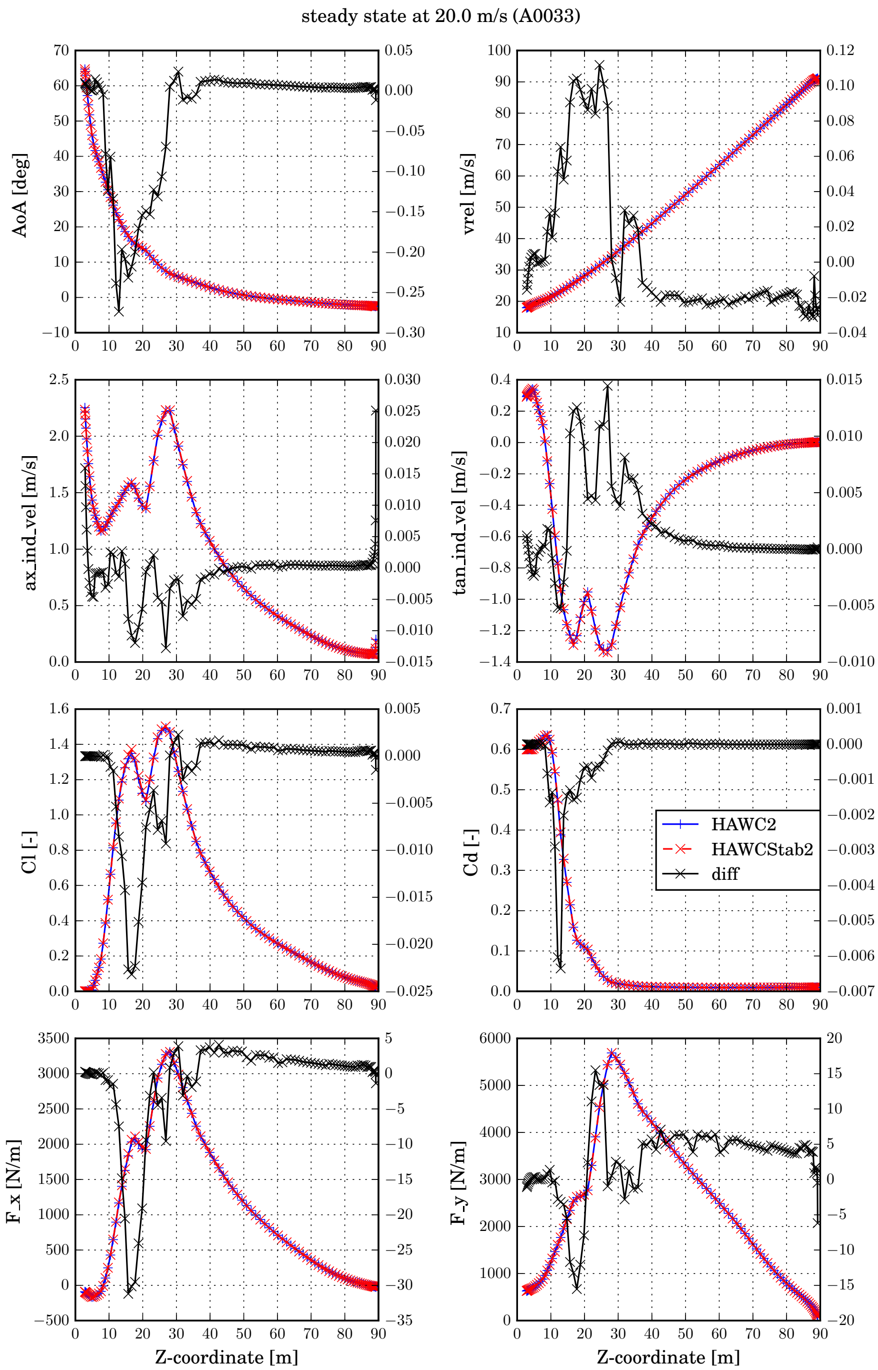

Figure 17: Blade load distribution at 20 m/s

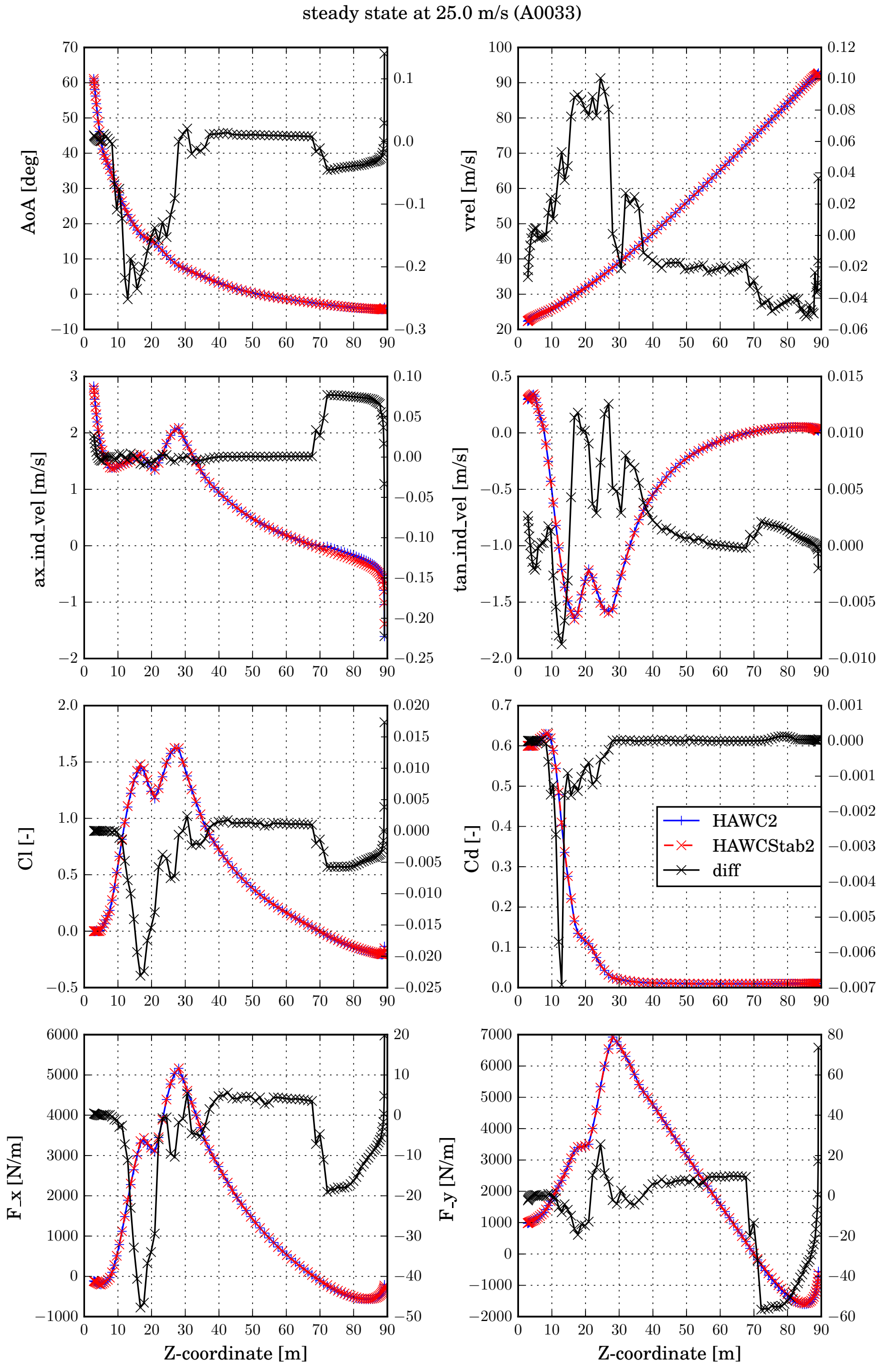

Figure 18: Blade load distribution at 25 m/s

2.4 Case 4: Flexible Blades and "Induction Only"

For this case the Prandtl tip correction model is switched off in order to assure that it is not related to the observed differences at the blade outboard region for high wind speeds (and negative axial induced velocities at the outboard blade region). Based on figure 20 it is suggested that the observed discrepancy is not dependent on the tip correction model: the same trends can be found compared to case 3 (see Figure 18). When zooming in on the the blade outboard region (see Figure 19), the HAWC2 results show that when the induction goes from positive to negative a "kink" in the distribution occurs, but closer to the tip both HAWC2 and HAWCStab2 axial induced velocities are, apart from a near constant, the same again.

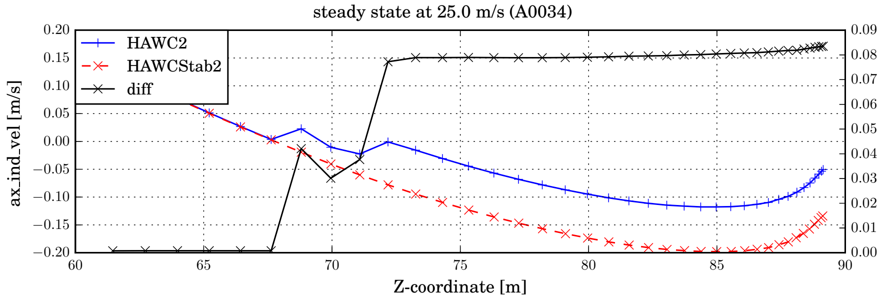

Figure 19: Axial induced velocity at 25 m/s for the blade outboard region.

This "kink" is caused by the thrust-induction relationship used within HAWC2. A polynomial expression was fitted on results from momentum theory and actuator disc simulations at high thrust coefficients [9]. However, the actual polynomial expression has a small zero order term (k_0) that would result in a non-zero c_t at zero induction a_x. Since the same expression is used (Equation 1), but mirrored, for negative induction there is a non-continuity when going from positive to negative values for c_t (see Figure 21) in HAWC2. The polynomial used in HAWCStab2 is the same as in HAWC2, but for negative values of c_t the curve is not mirrored (Equation 2). Future versions of HAWC2 and HAWCStab2 will use exactly the same relationship (Equation 1), but with $k_0 = 0$ in order to avoid a discontinuity around zero thrust/induction. The higher order terms are then re-fitted to the original curve. The relative difference between the original (with $k_0 \neq 0$) and updated curve ($k_0 = 0$) is given in Figure 22. Table 1 lists the current and updated coefficients of the polynomial.

$$a_x = \left(k_3 \cdot |c_t^3| + k_2 \cdot c_t^2 + k_1 \cdot |c_t| + k_0\right) \frac{|c_t|}{c_t} \quad (1)$$

$$a_x = k_3 \cdot c_t^3 + k_2 \cdot c_t^2 + k_1 \cdot c_t + k_0 \quad (2)$$

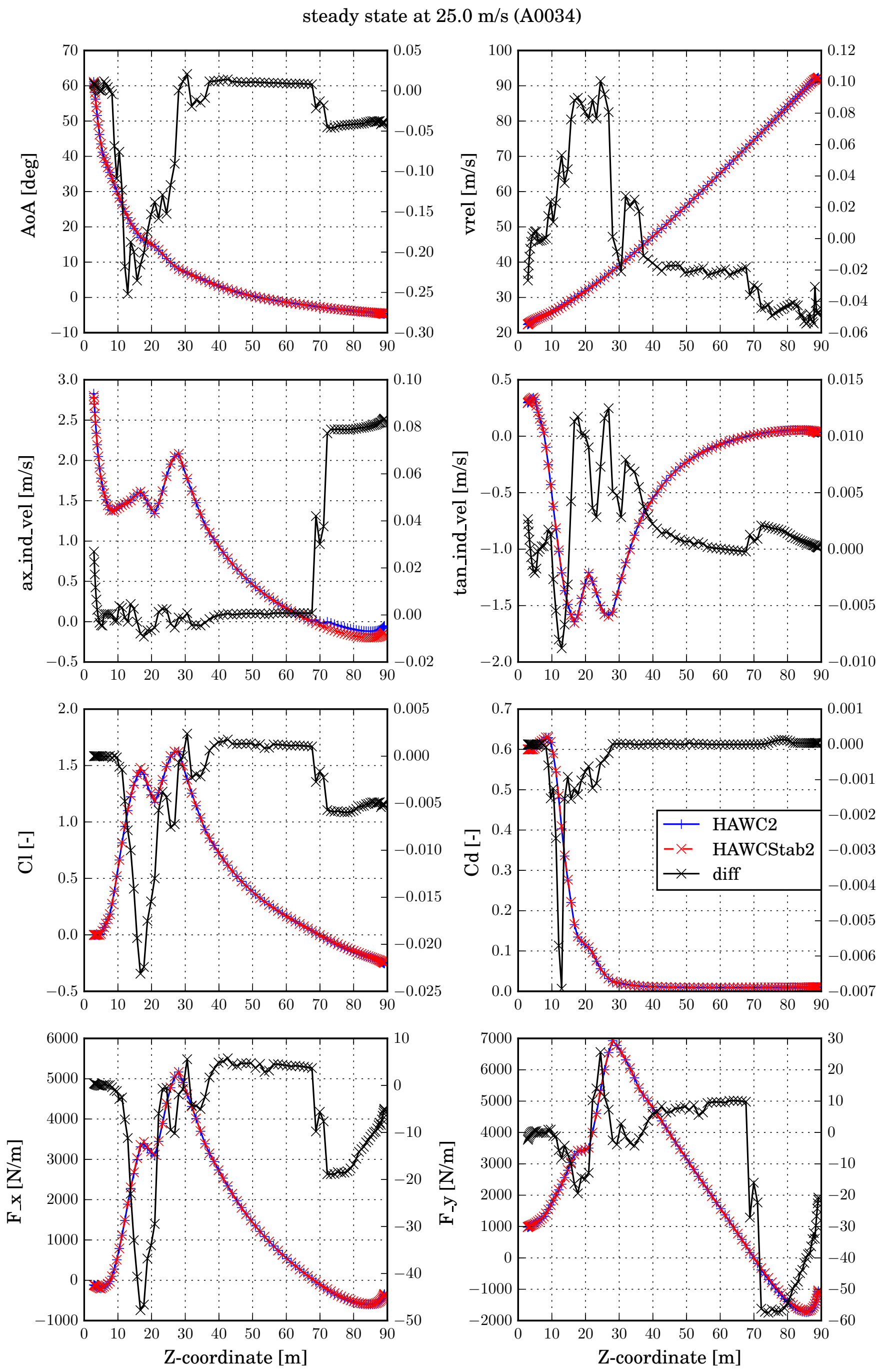

Figure 20: Blade load distribution at 25 m/s

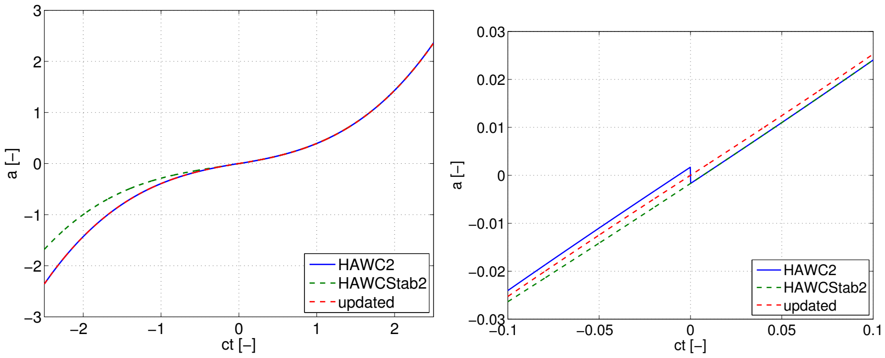

Figure 21: Axial induction as function of thrust coefficient: polynomial expression as used in HAWC2 v12.2 and HAWCStab2 v2.12.

coefficient	H2 $\leq$ v12.2 HS2 $\leq$ v2.12	updated
k_3	0.0892074	0.088251
k_2	0.0544955	0.058593
k_1	0.2511630	0.246040
k_0	-0.0017077	0.000000

Table 1: Coefficients for the c_t vs a_x polynomial as used for different versions in HAWC2 (H2) and HAWCStab2 (HS2). The updated coefficients will be used in versions 12.3 and 2.13 of HAWC2 and HAWCStab2. These versions are at the time of writing not yet released.

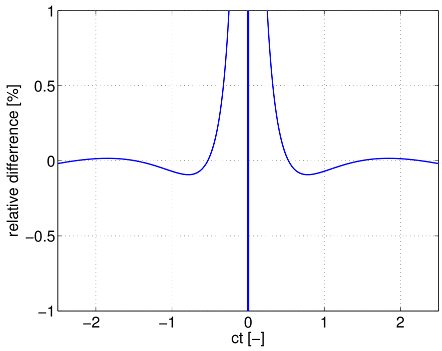

Figure 22: Relative difference of the thrust-induction polynomial as given in Equation 1 when using the current and updated coefficients given in Table 1

3 Conclusions

This report discussed the differences of the aerodynamic performance and loading of the DTU10MW reference turbine using steady state results between HAWC2 and HAWCStab2. There is a consistently good agreement between HAWC2 and HAWCStab2 for both the rotor integrated forces as well as for the distributed blade performance parameters. The small differences that have been noted can be summarized as follows:

- Integrated rotor performance parameters (rotor power and thrust) differences are below 1%.
- Distributed blade parameters show a small difference at the inboard sections which are caused by a small issue with the geometry input definitions in HAWC2. The next HAWC2 version is expected to resolve this issue.
- The Prandtl tip correction model introduces a small discrepancy at the tip. This issue is referred to future work.
- When the axial induction is negative (for high wind speeds at the blade outboard region) results diverge slightly due to differences between the relationship between c_t and the axial induction a_x. Future versions of HAWC2 and HAWCStab2 will use the same, continuous relationship between c_t and a_x.

Finally, it is concluded that the steady state performance computations of HAWCStab2 v2.12 are very close to the steady state simulation results of HAWC2 v12.2. Minor differences, who do not show to affect the steady state performance of the DTU10MW in a significant manner, are to be addressed in future version comparisons.

4 Future Work

Future comparisons should consider the following additional parameters:

- Rotor blade deflections (flap, edge and torsion)
- Tip correction model
- Aerodynamic torsion moment
- Structural eigenfrequencies at standstill

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