

General comments

The manuscript compares the radial induced velocity from two engineering models for a non-planar rotor based on the NREL 5 MW reference rotor: the Madsen model [1, 2] and a vortex cylinder (VC) model [3] as implemented by the authors in the KSS-Blade code [4]. It examines differences in the local distributions of radial induced velocity and in the corresponding integrated power effects. It also studies the behavior of the VC radial induced velocity near the blade tip under grid refinement, including the effect of a numerical cap used in the elliptic integral evaluation. These are interesting and relevant questions for the application and verification of engineering models for non-planar rotors, and I thank the authors for bringing attention to them. In my view, however, the present analysis and implementation do not yet fully support the manuscript’s aerodynamic interpretation and quantitative conclusions.

My assessment is based on three main points. First, the reported increase in tip radial velocity is obtained as the outermost calculation point moves progressively closer to the tip. However, this does not demonstrate a failure of the solution to converge at a fixed blade radius. Second, the power calculation includes only the radial part of the non-planar VC induced velocity and omits the axial induction contribution, which largely cancels the radial velocity contribution to power. Third, the KSS-Blade implementation used by the authors in this study contains inconsistencies in the momentum balance, torque integration, and radial force sign convention that affect the reported non-planar results.

AC1 responds to several of the concerns raised in CC1: it withdraws the claim that the close agreement between the Madsen and VC models in their integral power effects is systematic rather than coincidental; it reports that the sectional loads are grid converged, and it presents results from a broader parameter study. The formulation issues identified below remain unaddressed in the AC1.

Materials considered

This comment considers the submitted manuscript [5], the community comment CC1 [6], and the authors’ response AC1 [7]. It also uses the V5 version of KSS-Blade [4], including the code, input files, Python grid script and accompanying report made available through the GitHub repository cited in the manuscript’s code and data availability statement.

The manuscript refers to the code as “KSS” and gives the GitHub address <https://github.com/Schaffarczyk/KSS/> in its Code and data availability statement. That address is not available. The repository used in this comment is <https://github.com/Schaffarczyk/KSS-Blade/>. I therefore use the name KSS-Blade throughout this comment.

The reference calculations can be reproduced closely, despite small offsets. Source code inspection is important here because several quantitative results depend on implementation details that are not fully described in the manuscript.

The reference case described in the manuscript and the grid study were reproduced from the available KSS-Blade files. Independent checks were then carried out with the BEVC code, which combines a BEM solution with the vortex cylinder model of Li et al. [3], together with prescribed circulation tests and controlled source code level modifications to the KSS-Blade BEM formulation.

AC1 states that the additional calculations used the same code, that a supplement containing numerical results and three new figures accompanies the response, and that scripts and raw results will be added to the repository. These materials were not available to me at the time of this comment, so I could not verify these additional AC1 results.

Specific comments

The analysis of the VC radial induced velocity near the blade tip is useful primarily as a code verification exercise. The uncapped elliptic integral kernel reproduces the expected logarithmic increase when a calculation point approaches a vortex cylinder whose strength is held fixed. The authors showed that the numerical cap applied in the Fortran routine used to evaluate the elliptic integral can suppress this increase. However, this result does not, by itself, show a general failure of the cited VC formulation to converge.

The manuscript evaluates the change in power produced by adding the radial induced velocity to the BEM solution. However, in the complete VC formulation, a non-planar rotor not only has a radial induced velocity that is absent from the momentum theory, but also the axial induced velocity is different compared to a planar rotor. This change in axial induction is omitted in KSS-Blade. Its contribution to power is of comparable magnitude and opposite sign and largely cancels the radial velocity contribution.

In addition, the KSS-Blade implementation contains some inconsistencies in the treatment of the non-planar rotor that affect the reported power results. The reported percentages therefore reflect only the radial velocity contribution and are also affected by these implementation inconsistencies. They should not be interpreted as the complete effect of non-planar rotor trailed wake on power.

Radial velocity near the blade tip under grid refinement

In the manuscript, the vortex cylinder model is discretized uniformly along the blade radius into N annular sections. The outermost calculation point is located at the midpoint of the last annulus,

$$r_N = R - \frac{\Delta r}{2} = R \left(1 - \frac{1}{2N} \right). \quad (1)$$

Increasing N changes both the radial discretization and the location at which the outermost value is evaluated. As the grid is refined, the outermost calculation point moves closer to the tip vortex cylinder. The reported values of u_r at the outermost section are therefore evaluated at different radial positions, rather than at one fixed blade radius. For a vortex cylinder of fixed strength, its contribution to the radial induced velocity increases logarithmically as the calculation point approaches the cylinder. As described in the manuscript, the uncapped elliptic integral kernel reproduces this behavior, while the numerical cap in the Fortran elliptic integral routine can suppress it.

To examine how this behavior depends on the circulation distribution near the blade tip, I used the following family of symmetric prescribed circulation profiles. With $x = r/R$,

$$\xi = \min\left(\frac{x}{w}, \frac{1-x}{w}, 1\right), \quad \frac{\Gamma(x)}{\Gamma_{\max}} = [1 - (1 - \xi)^2]^q, \quad (2)$$

where w is the root and tip taper width, expressed as a fraction of the rotor radius, and q controls how rapidly the circulation approaches zero toward the root and tip. The circulation is constant at $\Gamma_{\max}$ between the two tapered regions. Figure 1 shows the profiles used in the grid refinement study of Figs. 2 and 3.

The prescribed circulation study follows the original VC formulation of Li et al. [3]. In that formulation, the annulus induction a_∞ is used to determine the vortex cylinder tangential vorticity strength γ_t , while the blade induction a_B is evaluated separately after applying the tip-loss factor F :

$$\begin{aligned} a_\infty &= f_{a-C_T}(C_{T,KJ}), & a_B &= f_{a-C_T}(C_{T,KJ}/F), \\ \gamma_{t,k} &= 2U_0(a_{\infty,k} - a_{\infty,k-1}). \end{aligned} \quad (3)$$

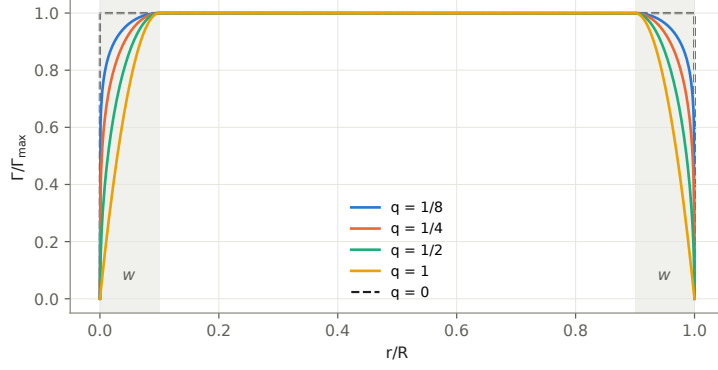


Figure 1: Prescribed circulation profiles of Eq. (2) used in Figs. 2 and 3. The tapered profiles have $w = 0.10$ and $q = 1/8, 1/4, 1/2$ and 1 ; the shaded bands are the root and tip tapers. For $q = 0$ (dashed), the circulation is constant up to the root and tip.

Here, f_{a-C_T} denotes the relation between axial induction factor and thrust coefficient.

Near the tip, Eq. (2) gives $\Gamma \sim (1 - x)^q$, and the prescribed local loading $C_{T,KJ}$ has the same leading-order behavior. Here, the $a - C_T$ relationship used in the study is the polynomial as implemented in the HAWC2:

$$f_{a-C_T}(C_T) = 0.0883C_T^3 + 0.0586C_T^2 + 0.2460C_T = 0.2460C_T + O(C_T^2), \quad (4)$$

so $a_\infty \sim (1 - x)^q$ near the tip. At the outermost midpoint,

$$a_{\infty,N} \sim N^{-q}, \quad \gamma_{t,\text{tip}} \sim a_{\infty,N} \sim N^{-q}. \quad (5)$$

Combining $\gamma_{t,\text{tip}} \sim N^{-q}$ with the logarithmic growth as the outermost evaluation point approaches the tip vortex cylinder gives

$$u_{r,\text{tip VC}}(r_N) \sim N^{-q} \ln N. \quad (6)$$

For $q > 0$, the contribution from the tip vortex cylinder tends to zero as the grid is refined, while the total radial induced velocity approaches a finite value. For $q = 0$, which is the case that the tip vortex cylinder strength remains constant as the grid is refined, then its contribution increases logarithmically as N increases.

To relate the parameter study to the NREL 5 MW rotor used in the manuscript, I fitted Eq. (2) to its circulation distribution from mid-span to the blade tip. The best fit gives

$$w = 0.1011, \quad q = 0.5930. \quad (7)$$

Of the tested cases, $w = 0.10$ and $q = 0.5$ is closest set of parameters.

The prescribed circulation study is not a reproduction of the manuscript's Figure 2. For the results shown in the manuscript, the KSS-Blade induction distribution $a_B(r)$ calculated at $N = 70$ resolution is kept fixed and interpolated onto finer grids before recalculating the VC velocity. In the present study, $\Gamma(r)$ is prescribed and the vortex cylinder strengths are calculated from a_∞ following Li et al. [3]. The two studies therefore use different vortex cylinder strengths near the blade tip.

The different behavior originates from how the vortex cylinder strengths are constructed. KSS-Blade uses the blade induction a_B instead of the annulus induction a_∞ to calculate γ_t , contrary to Eq. (3). In the KSS-Blade grid study, the outer value of a_B is kept fixed as the grid is refined, so the tip vortex cylinder strength is kept constant as N increases. This corresponds to $q = 0$, which results in the logarithmic increase in u_r . In the present study, for the prescribed circulation cases with $q > 0$, the tip vortex cylinder strength decreases as N increases.

Figure 2 shows the radial velocity at the outermost midpoint under grid refinement for $w = 0.10$ and different values of q on a planar rotor, with the vortex cylinder strengths calculated from a_∞ following Li et al. [3]. All tested $q > 0$ cases approach finite limits. For $q = 0$, the tip vortex cylinder strength is unchanged by grid refinement and the radial induced velocity continues to increase logarithmically. The results for $w = 0.20$ show similar behavior. Repeating the calculation for a 10° upwind cone gives the same behavior.

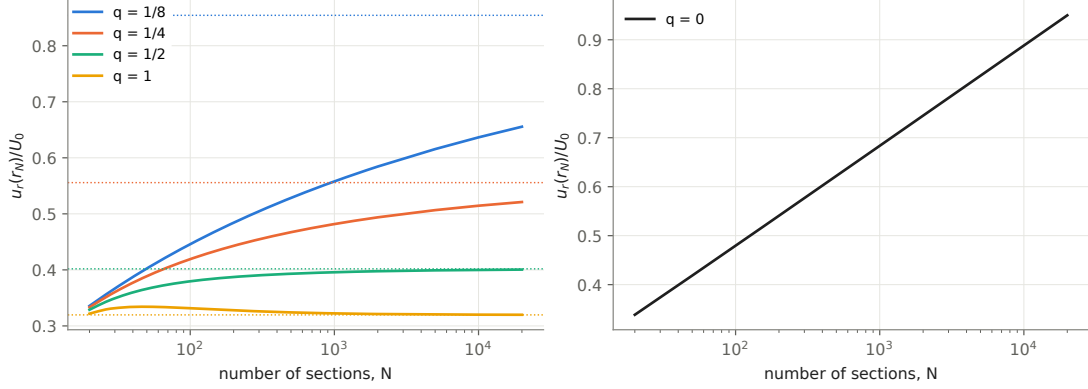


Figure 2: Radial velocity at the moving outermost midpoint for prescribed circulation profiles on a planar rotor. Left: for $w = 0.10$, all tested $q > 0$ cases approach finite limits, shown as dotted lines, although small q converges slowly. Right: for $q = 0$, the tip vortex cylinder strength is unchanged by grid refinement and the radial induced velocity increases logarithmically.

Figure 3 compares the radial velocity at fixed locations using 20 and 50 sections against a 10 000-section reference for $w = 0.10$. For $q = 1/2$, the error at the tested fixed radii from $0.5R$ to $0.8R$ is below 0.3% with 20 sections, and from $0.5R$ to $0.9R$ it is below 0.4% with 50 sections. Noticeable differences are limited to the last few sections near the root and tip. For $w = 0.20$, the behavior is similar, but the differences near the tip extend further inboard because the tip taper begins at $0.8R$.

AC1 appropriately narrows the interpretation of this grid study and states that the sectional loads are grid converged. The supporting scripts and sectional results should be provided for independent verification.

More importantly, the logarithmic increase found in the manuscript should not be interpreted as a general grid dependence of the VC formulation of Li et al. [3]. It occurs because, in the KSS-Blade grid study, the tip vortex cylinder strength remains fixed as the grid is refined while the outermost evaluation point moves progressively closer to that cylinder. When the circulation decreases smoothly to zero toward the blade tip and the vortex cylinder strengths are calculated following Li et al., the radial induced velocity converges under grid refinement. The manuscript’s grid study is therefore useful for identifying a numerical issue in the KSS-Blade implementation, but it does not show that the general VC formulation has a convergence problem near the blade tip.

The radial induced velocity contribution to power is not the complete VC result

The manuscript applies the Madsen and VC radial induced velocities after BEM convergence, while keeping the axial induced velocity unchanged. For the VC model, this includes only the radial induced velocity contribution and is therefore not the complete non-planar VC model of Li et al. [3], which also includes a change in the axial induced velocity.

The following Kutta–Joukowski analysis, as performed by Li et al. [8], considers only the contribution of the lift force to power. Here and below, *dihedral* refers to out-of-plane blade geometry in

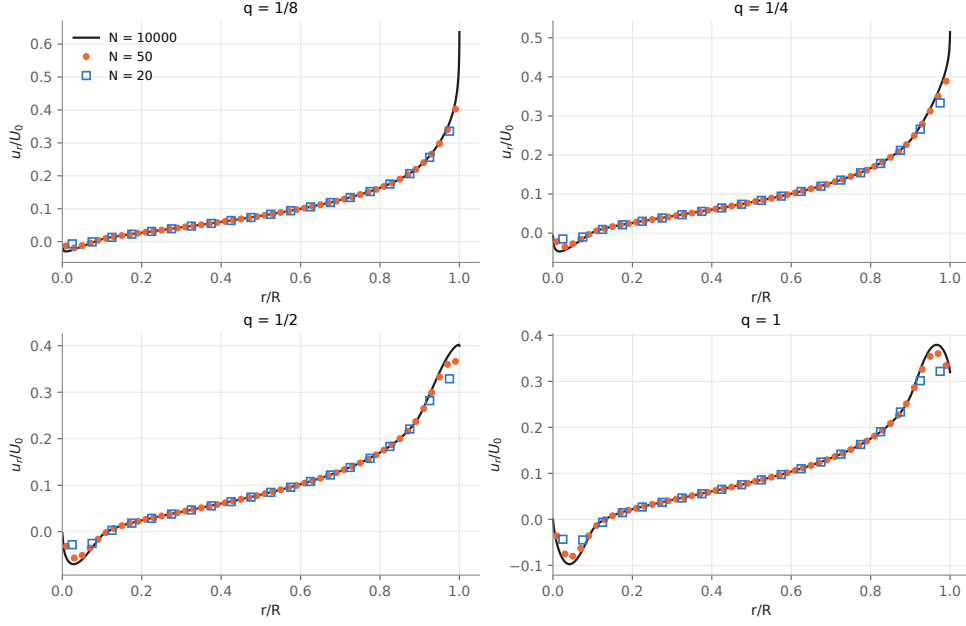


Figure 3: Radial distribution of the radial velocity for a planar rotor with prescribed circulation profiles of taper width $w = 0.10$. From upper left to lower right, $q = 1/8, 1/4, 1/2$, and 1 . With 20 or 50 sections, the velocity already follows the converged profile well, except for the last few sections near the tip and root.

the rotor plane, including blade prebend or elastic deflection as well as rotor coning; blade sweep is not considered. The local dihedral angle κ is measured relative to the rotor plane, with $\kappa > 0$ for upwind dihedral.

For a blade with dihedral, the tangential component of the lift force per unit blade span is

$$f_{L,x}^{\text{BL}} = \rho \Gamma [U_0(1 - a_B) \cos \kappa + u_r \sin \kappa]. \quad (8)$$

The corresponding power contribution is

$$dP = N_B \Omega r f_{L,x}^{\text{BL}} ds, \quad (9)$$

where N_B is the number of blades and Ω is the rotor speed. Using $dr = \cos \kappa ds$, Eq. (9) can equivalently be written as

$$dP = N_B \rho \Omega \Gamma r [U_0(1 - a_B) + u_r \tan \kappa] dr. \quad (10)$$

For a prescribed circulation distribution $\Gamma(r)$, the change relative to a planar rotor with the same $\Gamma(r)$ is therefore

$$\Delta P_{\text{VC}} = N_B \rho \Omega \int_0^R \Gamma(r) r [-U_0 \Delta a_B(r) + u_r(r) \tan \kappa(r)] dr, \quad (11)$$

where $\Delta a_B = a_{B,\text{np}} - a_{B,\text{pl}}$. The first term is the contribution from the change in axial induction, while the second is the radial induced velocity contribution. The radial term alone therefore represents only one contribution to the power change associated with the VC induced velocities.

I evaluated the two contributions in Eq. (11) for three prescribed circulation profiles, $(w, q) = (0.10, 0.5)$, $(0.10, 1.0)$ and $(0.20, 0.5)$, using a straight blade with a constant 10° cone and smooth prebend shapes with tip dihedral angles up to 30° . Across all tested profiles and shapes, the radial term alone gives a power change of 1.60–7.04%, whereas the combined axial and radial

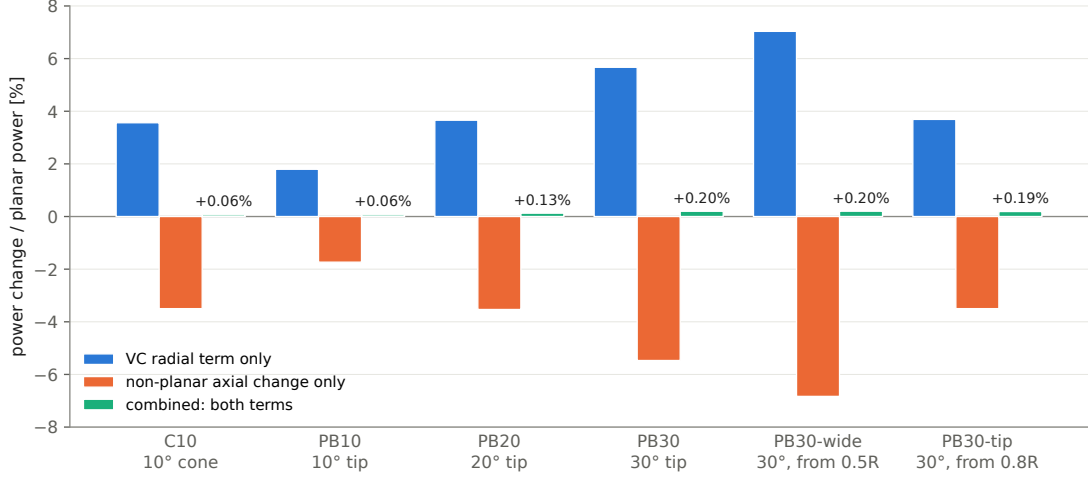


Figure 4: Power change at prescribed circulation with $(w, q) = (0.10, 0.5)$ for six upwind blade shapes. C10 is a constant 10° cone. PB10, PB20 and PB30 are smooth prebend shapes from $0.65R$ to the tip with tip dihedral angles of 10°, 20° and 30°; PB30-wide and PB30-tip have a 30° tip dihedral angle with prebend starting at $0.5R$ and $0.8R$, respectively. The radial VC contribution (blue) is largely cancelled by the non-planar axial contribution (orange), leaving a much smaller combined change (green).

contribution is only 0.062–0.297%, or 1.7–8.2% of the radial-only result. Figure 4 illustrates this cancellation for six shapes with $(w, q) = (0.10, 0.5)$.

These prescribed circulation calculations show that the radial induced velocity contribution can be much larger in magnitude than the combined axial and radial VC contribution because it is largely cancelled by the change in axial induction. The power changes due to the radial induced velocity in the manuscript and AC1 therefore do not represent the complete power change predicted by the non-planar vortex cylinder model.

Implementation issues in the supplied KSS-Blade non-planar formulation

For the authors’ 6 m downwind reference case at 11 m s^{-1} and 12.1 rpm, the supplied KSS-Blade source closely reproduces the separate contributions reported in the manuscript’s Table 1 and the AC1 decomposition. The deflected geometry reduces power by about 68 kW, while the Madsen and VC radial induced velocity contributions add about 75 and 77 kW, respectively. The reproduced contributions agree with the AC1 values to within 0.1, 0.6 and 1.6 kW.

For the same rotor and operating conditions, I also calculated the axial and radial VC contributions using the circulation from the reproduced KSS-Blade solution. This circulation was held fixed, and the vortex cylinder strengths were calculated following Li et al. [3]. The corresponding power changes were calculated from the Kutta–Joukowski lift force, without changes in drag.

At the fixed KSS-Blade circulation, the axial and radial contributions are +92.25 and −91.84 kW, leaving a combined change of only +0.41 kW. The KSS-Blade calculation includes the radial contribution but omits the non-planar axial induction contribution.

Figure 5 compares the reproduced KSS-Blade contributions with an independent BEVC calculation for the same supplied geometry and operating conditions. The BEVC axial and radial power contributions are obtained by post-processing one converged full-model solution, with its circulation and drag force held fixed. The deflected baseline is evaluated by removing both VC velocity contributions from that solution. Its power change relative to the planar reference, plus the axial and radial contributions, gives the total power change.

In KSS-Blade, the radial term is added after the BEM solution and does not change the circulation or drag. The KSS-Blade, manuscript and AC1 results omit the accompanying non-planar axial VC contribution.

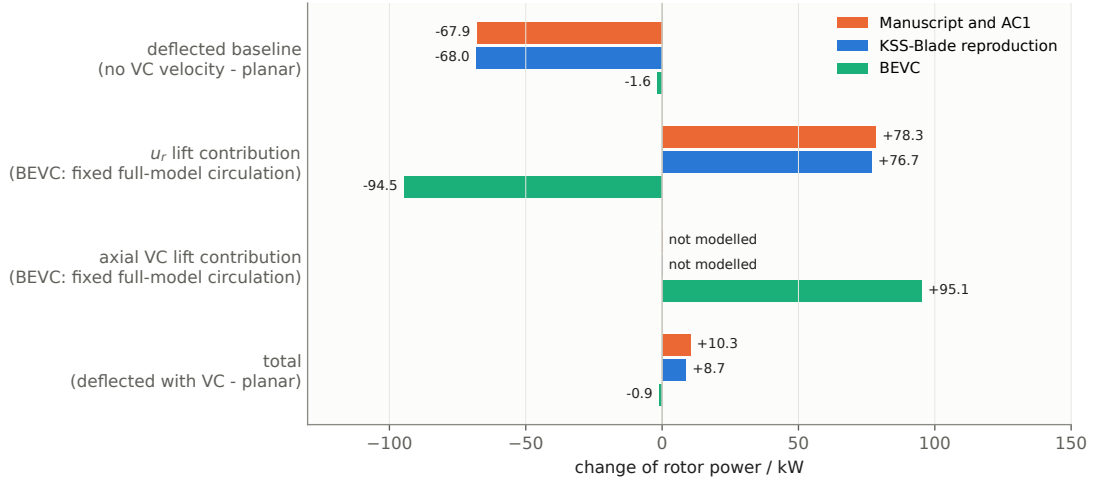


Figure 5: Power decomposition for the supplied NREL 5 MW geometry at 11 ms^{-1} , 12.1 rpm, and 6 m linear downwind deflection. The BEVC contributions are post-processed from one converged full-model solution. The baseline omits both VC velocity contributions, and the total is relative to the planar reference. The manuscript and AC1 values are from the authors' KSS-Blade calculations.

The remaining implementation issues discussed below concern the non-planar momentum balance, torque integration, and radial-force sign convention. The construction of the vortex cylinder strengths was discussed separately in the comment on the radial velocity near the blade tip; a brief note on the 6 m geometry is included in the additional comments.

Inconsistent momentum balance for a blade with dihedral

Consider a blade with dihedral and no blade sweep. Let r be the projected radial coordinate, ds the elementary blade length, κ the local dihedral angle, and U_0 the freestream velocity, so that

$$ds = \frac{dr}{\cos \kappa}. \quad (12)$$

Here, f_n is the section-normal force per unit blade length, V_{rel} is the relative velocity, ϕ is the section inflow angle, and F is the loss factor. The axial force and section velocity then satisfy

$$N_B f_n \cos \kappa ds = N_B f_n dr = 4\pi r \rho U_0^2 a(1-a)F dr, \quad (13)$$

$$V_{\text{rel}} \sin \phi = U_0(1-a) \cos \kappa. \quad (14)$$

With chord c , normal-force coefficient C_n , and $f_n = \frac{1}{2}\rho V_{\text{rel}}^2 c C_n$, the corresponding non-planar momentum equation is

$$\frac{a}{1-a} = \frac{N_B c C_n \cos^2 \kappa}{8\pi F r \sin^2 \phi}. \quad (15)$$

KSS-Blade uses the non-planar section velocity relation in Eq. (14), but retains the planar momentum equation without the $\cos^2 \kappa$ factor. The section kinematics and momentum balance are therefore not treated consistently. This produces an artificial change in axial induction and circulation when blade dihedral is introduced.

In the 6 m downwind reference case, correcting only the momentum balance reduces the power loss attributed to the deflected geometry from about 68 kW to about 25 kW. Thus, a large part of the geometry contribution shown by the supplied KSS-Blade formulation results from the inconsistent momentum balance rather than from the blade dihedral itself. Most of the remaining 25 kW results from the torque integration discussed in the next subsection.

Inconsistent torque integration along a blade with dihedral

Let f_t be the tangential force per unit blade length. For a blade element with local dihedral angle κ , the torque contribution is

$$dQ = N_B f_t r ds, \quad (16)$$

with $ds = dr / \cos \kappa$. KSS-Blade instead evaluates the torque using

$$dQ = N_B f_t r dr, \quad (17)$$

thereby integrating over the projected radial increment rather than the blade length.

In the 6 m downwind reference case, correcting this integration increases the power by approximately 23 kW without changing thrust or induction. When both the momentum balance and torque integration are treated consistently, the apparent power loss associated with the deflected geometry is reduced from about 68 kW to about 2 kW. This is comparable to the loss of 6.2 kW obtained with BEVC for the deflected geometry in Fig. 5. The large geometry contribution in the supplied KSS-Blade calculation is therefore mainly a consequence of these two formulation inconsistencies rather than a physical effect of blade dihedral.

Reversed sign of the radial-force contribution

Li et al. define $\kappa > 0$ for upwind dihedral [3, 9]. KSS-Blade uses the opposite convention, with positive dihedral angle downwind, so that its angle is

$$\tilde{\kappa} = -\kappa. \quad (18)$$

The radial contribution to the Kutta–Joukowski torque is proportional to

$$\rho \Gamma u_r \tan \kappa dr. \quad (19)$$

KSS-Blade inserts $\tilde{\kappa}$ into this term without reversing the sign. The radial-force contribution therefore has the opposite sign from that obtained with the convention of Li et al.

For the 6 m downwind reference case, the radial contribution decreases power when evaluated consistently with the Li et al. convention, but increases power in KSS-Blade.

Line-specific comments

1. Line 25: The introduction discusses both prebend and sweep, whereas the formulation considered in the manuscript appears to be restricted to out-of-plane geometry. If blade sweep is not included in the present formulation, this should be stated explicitly and sweep should not be grouped together with prebend when describing the scope of the work.
2. Line 28: The angle κ is referred to as the "local cone angle of the deflected blade". For a general prebent or deflected blade, which could be combined with cone angle, this definition is confusing. I suggest using the more general term local dihedral angle, and defining its sign convention explicitly. Coning can then be treated as the special case of constant dihedral.

3. Line 86: The statement that “codes of this class will in general contain such guards” is too general. The manuscript shows the effect of this numerical guard in the present implementation, but does not establish that similar guards are common in other codes.
4. Line 109: The Code and data availability statement gives the GitHub address <https://github.com/Schaffarczyk/KSS/>, which is not available. The repository used for this comment is <https://github.com/Schaffarczyk/KSS-Blade/>. The code name and repository address should be updated in the manuscript.
5. Line 109 and Table 1: The available code and input files do not reproduce all submitted results. The local tip values are reproduced, but the reproduced thrust and power differ from the values in the manuscript’s Table 1 by about -0.42% and $+0.5\%$, respectively.
6. Line 62: The 6 m deflection is not fully defined in the manuscript. From the supplied KSS-Blade input and source code, it is a linear downwind deflection with the projected radial stations unchanged. It is therefore equivalent to a straight blade with about 5.7° downwind coning, but with the blade length increased because the projected tip radius remains 63 m. The manuscript indeed described $\kappa \approx 5.7^\circ$ along the blade, but it is confusing.
7. Line 61: The supplied rotor is a modified NREL 5 MW model. Its root radius is 0.3 m rather than the official hub radius of 1.5 m, and its blade description includes additional tip stations with the chord tapered to 0.010 m at 63 m. The manuscript should identify the rotor as modified and document the geometry changes, particularly near the root and tip.
8. Line 9, line 30, and line 47: When referring to the Madsen radial induced velocity model, the manuscript should cite the original sources [1, 2].

Use of AI tools

AI tools, including OpenAI’s ChatGPT 5.6 and 6.1 and Anthropic’s Claude Opus 5.5, were used to help understand, reproduce, and modify the publicly available V5 version of the KSS-Blade source code in the authors’ GitHub repository. Their use included code inspection and modification, numerical reproduction, and plotting. The reviewer designed the numerical checks, verified the code changes and results, and is responsible for the scientific analysis and assessment presented in this comment.

The reviewer drafted the initial version of this comment and revised it several times before using ChatGPT 5.6 solely for suggestions on language and wording.

References

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