Proceedings of ASME Turbo Expo 2011
GT2011
June 6-10, 2011, Vancouver, British Columbia, Canada

GT2011-45904

AERO-STRUCTURAL ANALYSIS OF WIND TURBINE BLADES WITH SWEEP AND WINGLETS - COUPLING A VORTEX LINE METHOD TO ADAMS/AERODYN

Dr. Mark E. Braaten
GE Global Research
Niskayuna, NY, USA

Dr. Arathi Gopinath
GE Global Research
Niskayuna, NY, USA

ABSTRACT
The FAST/ADAMS/AeroDyn system of codes has been widely used to perform the aero-structural analysis of conventional wind turbine blades. Recent advances in blade design involve the development of aeroelastic tailored blades with large amounts of sweep, and blades with winglets. However, the existing Blade Element Momentum (BEM) approach in AeroDyn is limited to straight blades and does not account for sweep or dihedral effects. The goal of this work is to obtain higher fidelity aerodynamic loads predictions for such advanced blade designs. A Vortex Line Method (VLM) for computing aerodynamic loads has been coupled to ADAMS through modification of the existing AeroDyn interface. The VLM approach adopted here adds fidelity by modeling the effects of sweep, dihedral, 3D wakes, and wake dynamics. An existing steady/unsteady VLM code with these capabilities was restructured to allow its integration with AeroDyn. The FAST routines from NREL, which are used as a preprocessor to ADAMS, and the ADAMS/AeroDyn interface itself, were also modified to create an ADAMS model that properly accounts for the curvature of the blade that occurs when large amounts of sweep or winglets are present.

The resulting ADAMS/VLM model was compared to the original ADAMS/BEM model for a straight blade and for a highly swept blade. The model was also applied to blades with pressure-side and suction-side winglet configurations. The BEM and VLM models give similar aero predictions for the straight blade, as expected. The induced twist and blade deformations are found to be more similar for the two methods than the aerodynamic loads. Computations were made for the blades with the winglets at different wind speeds and different pitch settings, and results were obtained for blade deflection, induced twist, and thrust and torque force distributions.

INTRODUCTION
Modern wind turbine designs contain three-dimensional aerodynamic features such as sweep and dihedral (winglets) to provide aero-elastic capabilities and improved aerodynamic efficiency. The goal of this work is to develop a higher fidelity method for predicting aero loads for wind turbine blades with such features. Sweep is a displacement of the blade axis in the plane of the rotor. An example of a wind turbine with a highly swept blade is illustrated in Figure 1 (a). This blade rotates clockwise when viewed from upwind and features forward sweep (in the direction of rotation) near the root of the blade and aft sweep near the tip. Figure 1 (b) shows a wind turbine blade with a winglet. The bending of the winglet out of the plane of the rotor is referred to as dihedral.

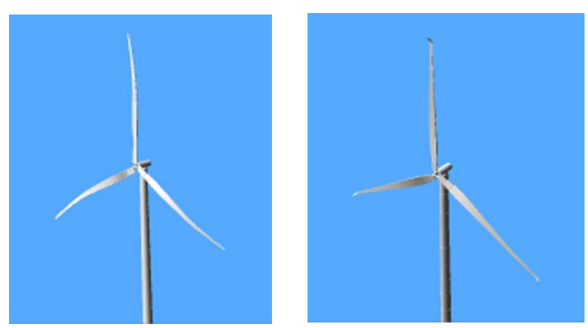

Figure 1 (a) highly swept blades, (b) blades with winglets

All wind turbine blades bend and twist as they experience wind loads. Aero-elastic blades may bend as much as several meters in the wind direction, and the induced twist can become large.

In order for the blade to perform at the optimal operating condition (angle of attack) and to avoid tower clearance issues, the blade is designed with a prebend and a pretwist. An accurate knowledge of the bending and induced twist caused by the wind loads is necessary to design the blade with the correct prebend and pretwist.

Traditional coupled aero-elastic analysis of wind turbine blades uses a beam model for the blade, and a simple aerodynamics model for computing the aero loads. Examples include FAST [1] or ADAMS [2], coupled with AeroDyn [3] for computing the aero loads. The Blade Element Momentum (BEM) - based aero model in AeroDyn, although adequate for straight blades, is not capable of capturing the effect of sweep or dihedral, and therefore is not adequate for blades with 3D aero features.

In the course of this work, various higher fidelity aerodynamics models have been explored to identify a suitable candidate for coupling with these beam structural models of the blade, to create a model capable of accurately predicting the aero loads on a blade with 3D features. The vortex line method (VLM) in [4]-[6] has been demonstrated to effectively capture the effects of sweep and dihedral by treating the blade as a curved lifting line that represents both the sweep and dihedral displacements. VLM methods also have the virtue of being much faster than alternative higher fidelity methods such as computational fluid dynamics (CFD), making them ideally suited as an alternate higher fidelity approach for coupled aero-elastic analysis.

METHODOLOGY

The Blade Element Momentum (BEM) theory is one of the two aero methods available in the AeroDyn interface to FAST or ADAMS. The second method, known as the Generalized Dynamic Wake (GDW) method, was not considered in this work, and we will focus solely on comparison of our VLM approach with the BEM model in AeroDyn.

In the BEM approach, the blade is divided spanwise into a number of independent 2D sections. The forces on each section are analyzed as a function of the rotor geometry, using 2D sectional lift and drag polars. These polars, illustrated in Figure 2 for a NACA0012 airfoil, are either measured experimentally in a wind tunnel or calculated using tools such as XFOIL [7].

The BEM method uses empirical root and tip loss models due to Prandtl, as well as other empirical corrections to model the effects at the finite ends of the blade. The BEM method has a number of limitations and assumptions [8]: 1) it neglects the vortical wake, 2) it neglects radial flow effects associated with centrifugal and Coriolis forces, and 3) it assumes the flow is quasi-steady. In [9] the BEM model in ADAMS/WT was applied to an aeroelastic model of a large wind turbine blade. The predictions from various empirical models introduced to alleviate some of the assumptions in BEM were compared.

In AeroDyn, each 2D section is independent, unaware of the presence or relative position of any other section – the method is hence incapable of distinguishing between a straight blade and a swept blade or a blade with winglets.

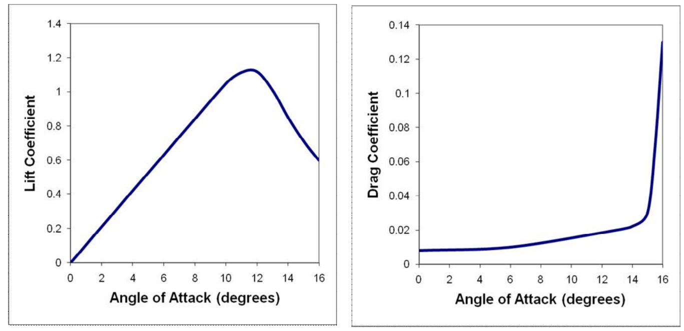

Figure 2 Lift and drag curves for NACA 0012 airfoil

Despite these limitations, BEM is still the standard wind turbine design method. Traditional straight, stiff blade designs do not incorporate large amounts of sweep or dihedral and the induced twist and bending effects are small. However, for the modern blades of interest here, with three-dimensional aerodynamic features, a higher fidelity method is needed.

Vortex line methods [4]-[6] represent the wind turbine blade as a series of bound vortices lying along a lifting line running through the quarter chord of the blade, and the wake behind the blade as a number of trailing vortices that trail behind the blade. The velocity field induced by the blade is computed via the Biot-Savart law.

The VLM method we are using here is closely patterned after the approach of Chattot et al [6]. The wake is modeled as a fixed cylindrical helix, the pitch of which is a function of the computed power coefficient. The fixed wake model in VLM captures the effects of the wake on the entire blade, including the root and tip, and does not require empirical root and tip loss models like the BEM approach.

The steady VLM procedure involves the following steps: for each blade section (on the lifting line) 1) compute the induced velocities u(y), v(y), w(y), 2) from these induced velocities, find the relative velocity and incidence angle, 3) from the drag polar get the lift coefficient C_l, 4) from the Kutta-Joukowski lift theorem, get the circulation Γ, and finally 5) use Γ in the Biot-Savart law to get the induced velocities resulting from the wake. This process, for a given fixed wake, is repeated until the circulation distribution converges. Then the wake is updated using the latest computed value of the power coefficient, and the whole process repeated until final convergence. The resulting solution yields the spanwise distributions of circulation, all three induced velocity components, angle of attack, lift and drag coefficients, as well as integrated quantities such as power and thrust coefficients.

The principal advantage of VLM over BEM for our application is that VLM senses the relative positions of the blade cross sections, and also sees the essential three-dimensional nature of the wake. In addition, no loss models at the hub and tip are employed by VLM, but the effect of these losses are captured through resolution of the wakes. This allows VLM to capture the true response to geometry modifications close to the tip like sweep and dihedral that BEM cannot.

Since VLM uses the same drag polars as BEM , it is expected for straight blades that the two methods will give similar results, and indeed this is borne out by practical experience. Since the VLM approach still uses 2D polars, it is expected that it won't be able to capture all three-dimensional phenomena, such as might occur with large amounts of sweep, or due to strong radial migration and unsteadiness due to flow separation [4]. However, studies performed at GE have shown that the VLM method models the effects of winglets on the aerodynamic performance of the blades nearly as well as CFD, and at a much lower cost. A detailed computational study involving a DOE with dozens of different pressure-side and suction-side winglets was performed. The computed distributions of torque and thrust force, and values of power and thrust coefficients were found to match closely in almost all cases, and the trends due to changes in winglet geometry were well captured [10].

Both FAST and ADAMS perform a beam-based structural analysis. However, FAST handles bending only and does not account for induced twist, whereas ADAMS can model both bending and torsional modes. In our work, FAST is used primarily as a preprocessor to generate the ADAMS input files. A more powerful finite element analysis code such as ANSYS is suitable for detailed structural analyses of composite shell models of the blade structure, but requires much more computational effort than the beam models.

Generally the level of structural and aero approaches should be similar for a balanced method. For our purposes here, namely to analyze blades with 3D aero features in a rapid design mode, we have selected ADAMS for the structural analysis and VLM for the aero analysis. ADAMS can capture the effects of induced twist which is vital for aero-elastic blades, whereas FAST cannot. VLM can capture the effect of sweep and dihedral, which BEM cannot. Detailed structural analyses using ANSYS, coupled with hybrid CFD approaches [11]-[12] appear promising, but are simply too time consuming for our design needs here.

Modifications to AeroDyn Interface

AeroDyn is used to compute the aerodynamic forces by both FAST and ADAMS, as well as some other software. An implementation strategy for VLM code coupling was identified that ensured that the VLM-related modifications are compatible with FAST as well as ADAMS. Although FAST does not handle induced twist, it was useful for testing and debugging purposes as the interface is fully available as Fortran source code, the FAST code runs very fast, and it does not require a software license.

As part of this process, it was necessary to modify the existing VLM code to allow it to be driven from AeroDyn in the same fashion as the built-in BEM model. AeroDyn loops over time, blades, and blade elements independently, returning the normal and tangential forces on the individual blade elements. This is suitable and natural for the BEM method, as each blade cross section is independently computed anyway. However, VLM needs to solve for all of the blade elements simultaneously, as they are coupled by the method, so this means of calling the VLM code is not totally straightforward. The strategy adopted for integrating the VLM code is to solve and store the solution for all of the blade elements when the first one is called, and then simply look up the solution for remaining elements from this stored database as they are visited. Some restructuring, and finer grain modularity of the VLM subroutines was required to accomplish this.

In addition to this restructuring, some additional work had to be done. The VLM method uses a cosine distribution of points along the blade to cluster the points near the root and tip regions, where the aerodynamic gradients are largest. ADAMS use blade elements that are nearly uniformly spaced along the blade. It was decided here to allow each code to use it own optimal mesh distribution, and to interpolate the results between the codes.

One additional wrinkle was that the VLM code interpolates the polars between the specified locations to the grid point locations, rather than using breakpoints to specify where the polars are applied, as done in the AeroDyn BEM model. AeroDyn imposes the polars in a piecewise constant manner up to a specified breakpoint, at which point the next polar takes over. We feel the use of interpolated polars gives a more realistic representation of the underlying geometry. The consequence of this difference in the AeroDyn interface is that a separate routine had to be written for the VLM option to compute the lift and drag forces on the blade elements using the interpolated polars. It was not in the scope of this work to modify the manner in which AeroDyn treats the polars for

BEM, either by modifying AeroDyn or by preprocessing the polars a priori.

The changes to AeroDyn to invoke the VLM routines were implemented as wrapper code to minimize the number of modifications made to the existing AeroDyn interface. The starting point was AeroDyn version 12.58 (28-June 2005), obtained from the NREL website [12].

During the coupled solution, communication occurs between ADAMS and VLM. The twist and pitch at each blade element are updated every time step and passed to the VLM code through AeroDyn. In the current implementation, induced deflections in sweep and dihedral are not updated for the aero computation as the blade deforms. The elemental forces passed back to ADAMS from VLM are based on the interpolated polars, consistent with the standalone VLM calculation, as mentioned earlier.

The new VLM option in AeroDyn requires only a few additional inputs. The VLM model is specified in the AeroDyn .ipt file through an additional VLM option to the InfModel input, which normally is used to invoke either the standard AeroDyn BEM model, or the optional AeroDyn GDW (Generalized Dynamic Wake) model. A separate block of VLM specific inputs is added at the end of the AeroDyn .ipt file. The sweep and dihedral distributions are input here. Defaults are used for those values that are not specified.

ADAMS requires a User dynamic link library (DLL) that runs along with the base code to invoke the AeroDyn interface. Our modified DLL that includes the VLM modifications to the AeroDyn interface was generated for MD ADAMS R3 using the Intel Fortran 9.1 compiler. In addition, for test cases with large memory requirements, ADAMS also requires the use of a custom memory model, which is provided in the form of an additional DLL.

Modifications to FAST/ADAMS Model

The FAST [1] preprocessor for ADAMS was developed and used for straight blades, and includes a number of assumptions appropriate for such blades. In particular, we found that significant modifications to both FAST and ADAMS/AeroDyn routines were necessary to properly model winglets. Similar challenges encountered while designing highly swept aeroelastically tailored blades using ADAMS/Aerodyn were reported in [14].

One such assumption in the NREL FAST is that the blade axes are assumed to form a small angle with the pitch axes, and a small angle transformation approximation is used. The presence of winglets can cause the blade axes to form large angles with the pitch axis, violating this assumption. To remedy this, the small angle transformation was replaced by a general transformation of axes. The CAD model of the winglet, the initial incorrect ADAMS model created by NREL FAST, and the final corrected ADAMS model are shown in Figure 3.

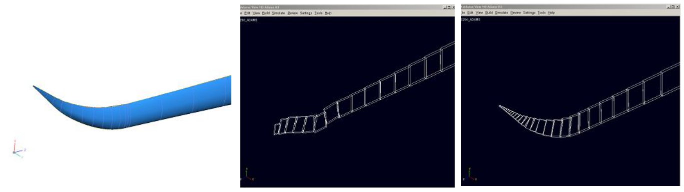

Figure 3 (a) Winglet CAD model (b) Original FAST/ADAMS model (c) Corrected FAST/ADAMS model

Once the FAST preprocessor had been corrected to properly create the winglet geometry, additional modifications were found necessary for the AeroDyn/ADAMS interface. One such modification involved the procedure for recovering the twist from the ADAMS markers, as the original procedure is adequate only for straight blades. Testing with rigid models showed that ADAMS was not returning the prescribed aero twist in the winglet region, as illustrated in Figure 4. A new procedure which accounts for the presence of the curvature of the winglet proved able to closely recover the initial prescribed twist distribution.

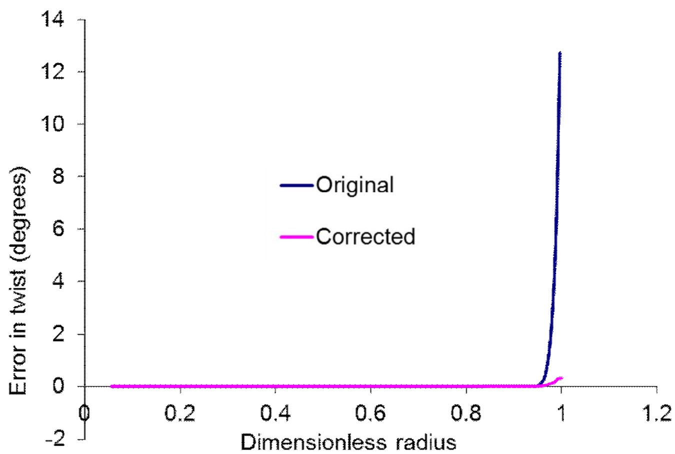

Figure 4 Aero twist recovered from original and corrected procedures

Aerodynamic Forces

The aerodynamic forces computed by the VLM code are passed to the ADAMS model by the AeroDyn interface. The VLM code internally computes the torque and thrust force distributions along the blade, using strip theory[4]. AeroDyn computes the aerodynamic torque and thrust on the blade by directly summing the forces and torques on the blade elements. Careful comparison of the resulting forces and torques showed them to be consistent within interpolation error, and a slight contribution from the radial induced velocity accounted for by the VLM code, which has a slight effect in the winglet region. To facilitate comparison in the results section between the BEM and VLM models, we have chosen to present the results based on the AeroDyn approach in this paper.

RESULTS

The focus in this paper is to compute the aerodynamic loads on various wind turbine blades under steady wind conditions, accounting for the structural bending and induced twist of the blades under load. Accordingly, we have considered only cases with constant wind speed, zero yaw, and have neglected tower effects and tilt of the rotor and coning of the blades, so as to achieve a steady-state aerodynamic solution. The VLM code is run in a steady-state mode, to reduce run time. A typical ADAMS/VLM run of this type takes approximately 3-5 minutes, compared to about 1-2 minutes for an ADAMS/BEM run. A simulation time of 60 seconds was run with a time step of 0.01 seconds, and the steady state results were taken from the end of the run.

Comparisons are made between the new ADAMS/VLM approach and the standard ADAMS/BEM approach. For cases without significant three-dimensional aerodynamic features, one would expect the results of the two methods to be comparable. For cases with large sweep and winglets, one would not expect the ADAMS/BEM results to be particularly accurate, due to the limitations of the BEM model described earlier. The BEM results for these cases are contrasted here to the results from the new ADAMS/VLM approach, since the differences give some sense of the magnitude of the aero effects caused by such features.

Straight NREL Test 12 Blade

The first case considered here is the straight-bladed NREL Test12 blade [15]. This case was run in FAST, for testing purposes, and to demonstrate that our implementation of VLM in the AeroDyn interface was fully general, and not tied to ADAMS. Figure 5 compares the power coefficient computed by FAST using both BEM and VLM, to the results obtained with our standalone VLM code. The steady VLM results are close to BEM for this straight blade, as expected. It proved essential for the AeroDyn routine that calculates the power coefficient RotCp to use consistent interpolated polars for the coupled VLM run, in order to match the standalone VLM results.

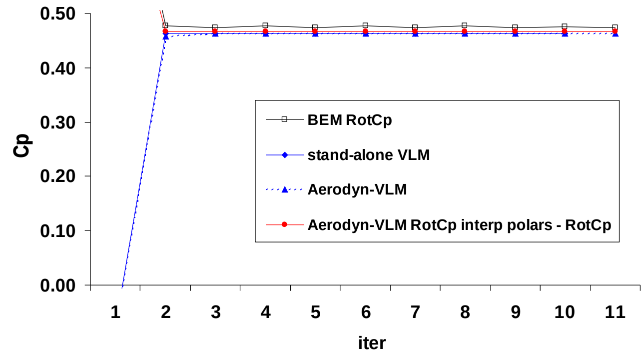

Figure 5 FAST NREL Test#12 straight blade case - Cp computed using BEM vs. VLM

Highly Swept Aero-elastic Twist Blade

In this section, the coupled ADAMS/VLM results for a highly swept AT blade are described. The initial focus was on a test case with a steady wind velocity. The goal was to compare the BEM and VLM results for power coefficient, tip deflections and twist, and the induced twist distribution along the blade. This early conceptual design of an AT blade is highly flexible, and has very little structural damping, which led to difficulties achieving a truly steady state solution. The computed tip deflections and induced twist are much larger for this case than for other cases that represent more conventional wind turbine blades.

Overall, the BEM and VLM methods give very similar results for this case. The evolution of the computed power and thrust coefficients, as a function of time, is shown in Figure 6. The solutions show marked unsteadiness, as the blade seems to resonate back and forth at a frequency somewhat higher than tower passing frequency. The aero coefficients reach an apparent periodic steady state after about 30 seconds of simulation time. VLM predicts slightly higher averaged power and thrust coefficients than BEM, as shown in Table 1.

Table 1 Aero coefficients

	%Diff (VLM – BEM)
C_p	1.4%
C_t	3.6%

(values averaged over the last two periods)

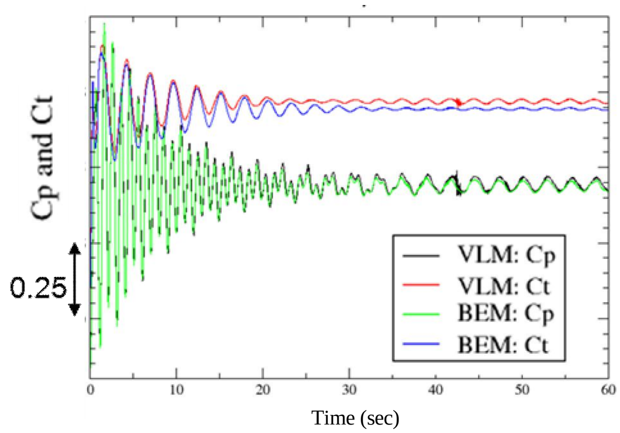

Figure 6 GE aero-elastic tailored swept blade: Evolution of Cp and Ct as predicted by BEM and VLM

Figure 7 shows the tip deflection and twist computed by VLM for this case. The flapwise and edgewise deflections appear to reach a periodic steady state sooner than the aero coefficients, after only about 10 seconds of simulation time. The edgewise deflection essentially oscillates about the blade's initial position. The persistence of the oscillations is due to slight oscillations of the supporting tower and the low level of damping in this design. The final induced twist computed by the two methods is also very close, and only differs by less than 0.1º.

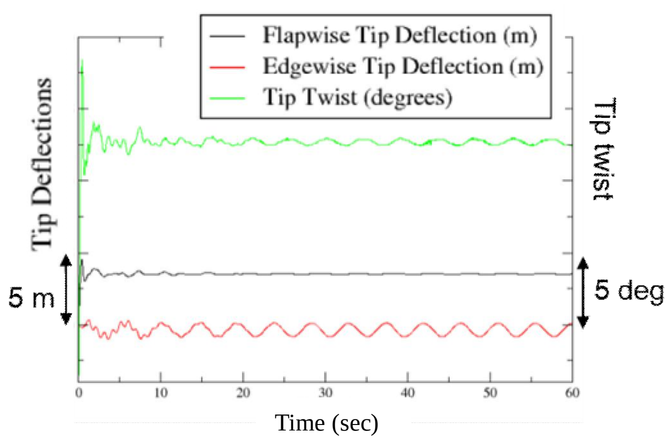

Figure 7 GE aero-elastic tailored swept blade: Evolution of tip deflection and tip twist as predicted by VLM

Blades with Winglets

In this section, we consider the results from some wind turbine blades with generic winglets. Both pressure-side (facing upstream away from the tower), and suction-side (facing downwind towards the tower) winglets were considered. Other than the presence of the different winglet, the blades considered are identical. In particular, the same distributions of chord, prebend and pretwist were imposed on the blades, along with the same structural properties.

Figure 8 illustrates the computed axial deflection of the blade with the pressure-side winglet at the rated wind speed. The initial prebend of the blade is seen from the initial picture, where the wind speed is zero. As the wind speed increases, the blades bend back towards the tower.

Recall that rotor tilt and coning of the blades has been neglected in order to reach a steady state aero solution; in reality a small tilt angle and a similar coning angle would provide adequate clearance between the blade and tower.

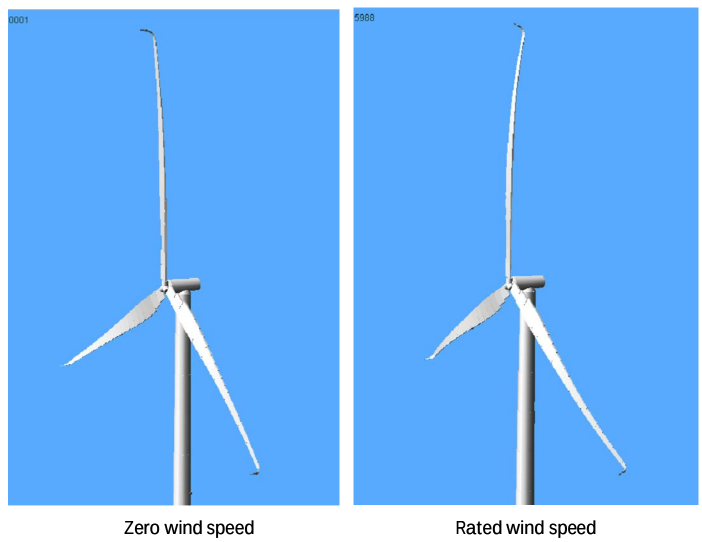

Figure 8 Computed blade deflection at rated wind speed

Figure 9 shows the evolution of the power and thrust coefficients for the two winglet cases, at a wind speed of 9 m/s and a pitch angle equal to zero degrees. The VLM method predicts somewhat higher power and thrust coefficients than BEM for both pressure-side and suction side winglet cases.

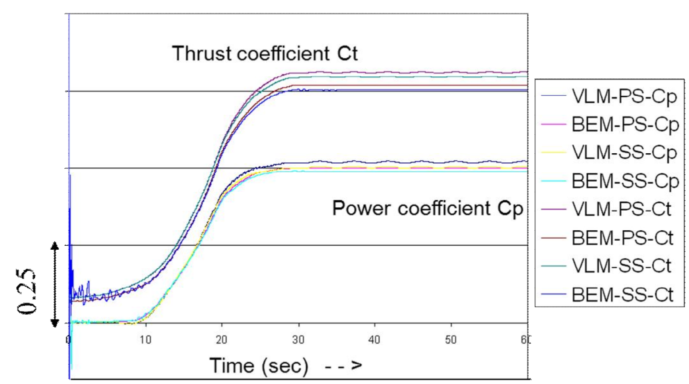

Figure 9 Evolution of Power and Thrust coefficients predicted by ADAMS/VLM and ADAMS/BEM for blades with pressure-side(PS) and suction-side(SS) winglets

Figure 10 shows the evolution of the tip deflection for the same cases. Both the VLM and BEM solutions show some oscillation at the tip; while this is much less than was seen earlier for the more flexible AT blade, it is still evident in this solution. The VLM aero results shown in Figure 9 show similar oscillations, while surprisingly the BEM results look completely steady. It appears that the VLM approach sees the oscillating motion of the winglet region, while the BEM approach does not.

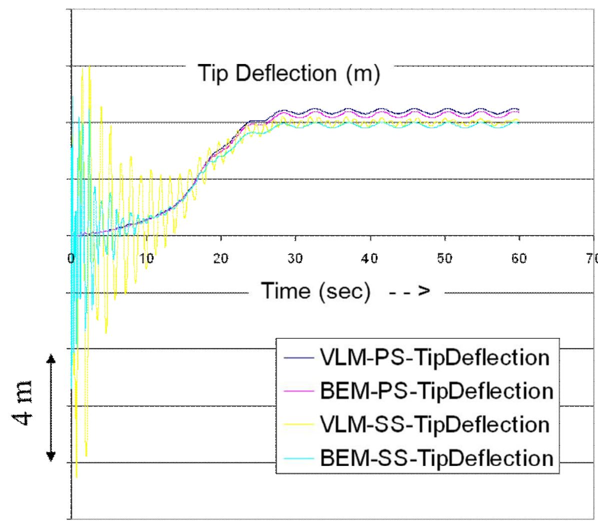

Figure 10 Evolution of Tip deflection predicted by ADAMS/VLM and ADAMS/BEM for blades with pressure-side and suction-side winglets

Figure 11 shows the ADAMS/VLM predictions for the blade with the pressure-side winglet at zero pitch angle, over a range of wind speeds.

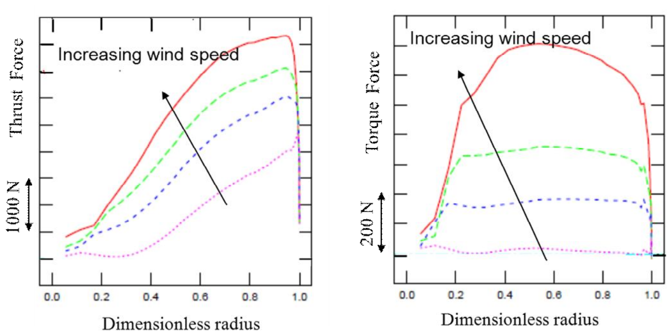

Figure 11 ADAMS/VLM predictions for blade witl. pressure-side winglets at 0° pitch, varying wind speed (a) thrust force, (b) torque force

As the wind speed is raised, the angle of attack and the lift and drag on the airfoil sections increase, and as a result the thrust and torque forces grow significantly. Despite the dramatic increase in aerodynamic loads with higher wind speeds, which leads to greater axial blade deflection, the induced twist doesn't change very much, and still ranges from 1-2 ° over most of the blade.

A close-up view of the induced twist in the winglet region, shown in Figure 12, shows that it varies only slightly by about 0.3° over the range of wind speeds studied. This result suggests that the induced twist may be coming primarily from inertial forces and not aero forces in this case.

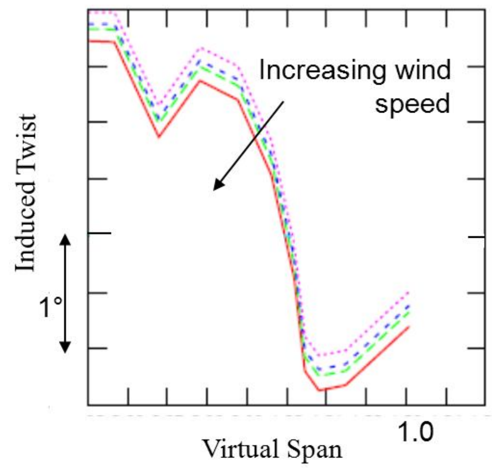

Figure 12 ADAMS/VLM predictions of induced twist for blade with pressure-side winglets at 0° pitch, varying wind speed, plotted in the winglet region

A series of ADAMS/VLM predictions was made for the blade with the pressure-side winglet at a wind speed of 9 m/s, for various pitch angle settings, ranging from 0 to -4 degrees. As the pitch angle became more negative, the angle of attack on the blade increased. Since the angle of attack was still below the stall point, except at the very tip, both the thrust and torque forces also increased. Again, the induced twist was found to be between 1-2 °, and nearly independent of the pitch angle over the range of angles tested.

Figure 13 and 14 show a comparison between VLM and BEM for the same case. The angle of attack predicted by the two methods are close over most of the entire blade, except in the winglet region, where BEM shows a much larger angle of attack, leading to a larger negative torque force. This is shown more clearly in Figure 14. Differences in the torque and thrust force distributions along the blade are also observed, and come primarily from the use of the interpolated polars in the VLM code (which lead to smoother solutions) and the stepwise polars in the BEM method (which lead to lumpy solutions).

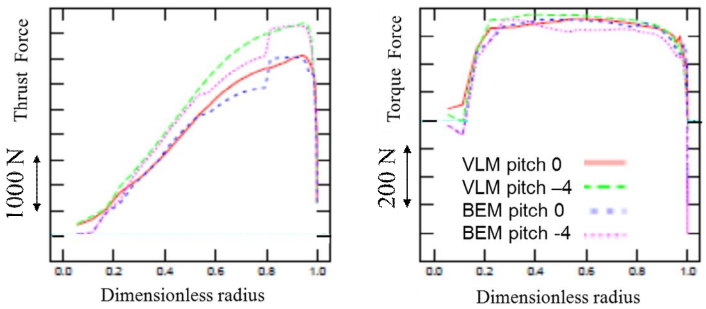

Figure 13 ADAMS/BEM vs. ADAMS/VLM comparisons for blade with pressure-side winglets at a wind speed of 9 m/s, pitch angles = 0, -4: plotting along blade length (a) thrust force (b) torque force

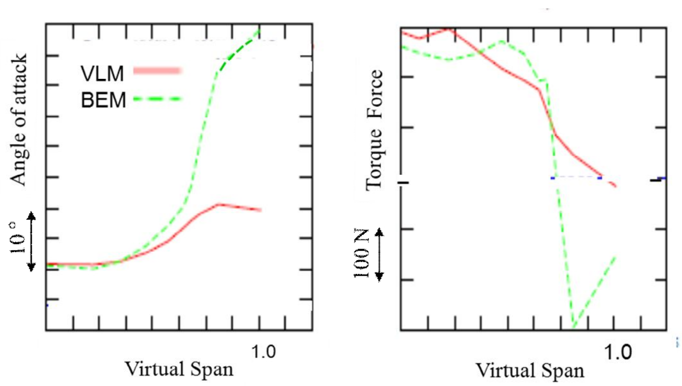

Figure 14 ADAMS/BEM vs. ADAMS/VLM comparisons for blade with pressure-side winglets at a wind speed of 9 m/s, pitch = 0: plotted in the winglet region (a) angle of attack (b) torque force

Figure 15 compares the VLM and BEM predictions for a similar suction-side winglet case. Again, the BEM method predicts a very different angle of attack than VLM in the winglet region, and consequently different thrust and torque forces.

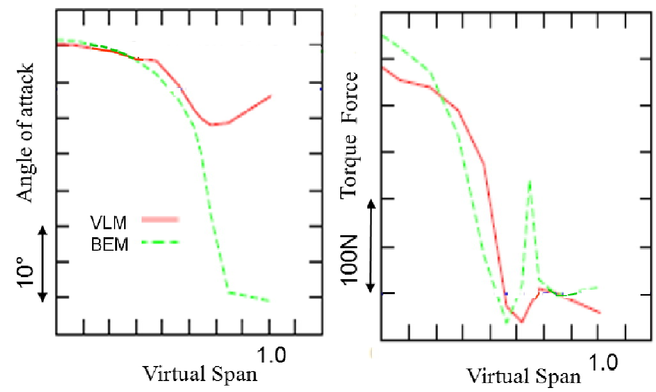

Figure 15 ADAMS/BEM vs ADAMS/VLM predictions for blade with suction-side winglets at a wind speed of 9 m/s, pitch = 0° , plotted in the winglet region (a) angle of attack (b) torque force

CONCLUDING REMARKS

This paper describes various challenges that were encountered and some of the steps taken to overcome them during the course of developing a higher fidelity method for predicting aero loads for non-straight wind turbine blades. A Vortex Line Method (VLM) code, capable of modeling effects of sweep, dihedral, 3D wakes, and wake dynamics, has been successfully coupled with ADAMS through a modification of the AeroDyn interface. In addition, limitations of using the standard FAST/ADAMS model for winglet configurations have been identified and the appropriate modifications have been discussed, such that the ADAMS aero markers are able to capture the required geometrical features of sweep and dihedral.

Results have been presented for steady wind conditions for various wind speeds and various pitch settings. While the detailed aerodynamic behavior in the winglet region differs significantly between the VLM and BEM results, the overall structural response computed by ADAMS (axial deflection and induced twist) is not very different.

In the current implementation, the aero calculation accounts for induced twist, but not induced deflections in sweep and dihedral, which will be addressed in the near future. We then plan to investigate cases with unsteady wind gusts, to see how the ADAMS/VLM method performs for such cases. The ADAMS/VLM method will ultimately be validated and fine-tuned against experimental data from GE machines. The current work is our first step towards obtaining higher fidelity aero loads in an aero-structural framework, which will enable detailed blade design at moderate computational costs.

ACKNOWLEDGMENTS

The authors would like to acknowledge collaboration on the VLM code with Professor J. J. Chattot at UC-Davis, and useful discussions and assistance from Brandon Gerber and Thomas Perley of GE Energy.

REFERENCES

[1] Jonkman, J. and Buhl, M. L., FAST User's Guide, NREL Technical Report NREL/EL-500-38230, August 2005.

[2] NWTC Design Codes (ADAMS2AD by Dr. David J. Laino and Jason Jonkman). http://wind.nrel.gov/designcodes/simulators/adams2ad.Last modified 12-August-2005; accessed 12-August-2005

[3] Moriarty, P. J., and Hansen, A. C., "AeroDyn Theory Manual", NREL/EL-500-36881, 2005.

[4] Chattot, J. J., "Helicoidal Vortex Model for Steady and Unsteady Flows"., AIAA Paper-AIAA-2004-0829, (2004).

[5] Hallissy, J. M. and Chattot, J. J., "Validation of a Helicoidal Vortex Model with the NREL Unsteady Aerodynamic Experiment", **Computational Fluid Dynamics Journal**, 14(3):30, October 2005, pp. 236-245 (2005).

[6] Chattot, J. J. , "Effect of Blade Tip Modifications on Wind Turbine Performance using Vortex Model", **Computers and Fluids**, Vol. 38, pp. 1405-1410, 2009.

[7] Drela, M., "XFOIL: An Analysis and Design System for Low Reynolds Number Airfoils", Conference on Low Reynolds Number Airfoil Aerodynamics, University of Notre Dame, also in "Low Reynolds Number Aerodynamics", T. J. Mueller (ed.), Lecture Notes in Engineering No. 54, Springer-Verlag, 1989.

[8] Schmitz, S., "Coupling of Navier-Stokes Solver with Helicoidal Vortex Model for the Computational Study of Horizontal Axis Wind Turbines", PhD Thesis, Department of Mechanical and Aeronautical Engineering, University of California, Davis, 2006.

[9] Shawler, J. R., “Engineering Aerodynamics of Horizontal Axis Wind Turbines”, Ph.D. thesis, Dept. of Electronic and Electrical Engineering, Loughborough University, 2004. http://hdl.handle.net/2134/7629

[10] Braaten, M. E., Sharma, A., Kanakala, V., and Chaudhury, L., "Unified VLM Code: TG6 Report Out", GE internal report, restricted distribution, 2010.

[11] Schmitz, S. and Chattot, J. J., "A Parallelized Coupled Navier-Stokes / Vortex-Panel Solver", **J. Solar Energy Engineering**, Vol 127, pp. 475-487, 2005.

[12] Braaten, M. E., Standish, K., Kolasa, S., and Gharaibah, E. “Implementation of a Hybrid Navier-Stokes / Vortex Panel Method for Wind Turbine Aerodynamic Analyses in CFX”, ANSYS International Conference, Pittsburgh, Pa, 2008.

[13] NREL website at http://wind.nrel.gov/designcodes/

[14] Global Energy Concepts, “Evaluation of Aeroelastically Tailored Small Wind Turbine Blade”, DOE Report DOE-001, 2005. http://www.osti.gov/bridge/servlets/purl/861425-iEvPW8/861425.pdf

[15] Jonkman, J. and Buhl, M. "New Developments for the NWTC's FAST Aeroelastic HAWT Simulator", 23rd ASME / 42nd Wind Energy Symposium, Reno, NV 2004.