



AeroDyn v15 User's Guide and Theory Manual

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Technical Report (Arial 11 pt Bold)
NREL/TP-xxxx-xxxxx
Month Year (Arial 11 pt)

Contract No. DE-AC36-08GO28308

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Prepared under Task No(s). XXXX.XXXX, XXXX.XXXX

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1 Nomenclature

Future versions of the manual will include nomenclature used throughout the document.

2 Introduction

AeroDyn is a time-domain wind turbine aerodynamics module that has been coupled into the FAST version 8 multi-physics engineering tool to enable aero-elastic simulation of horizontal-axis turbines. AeroDyn can also be driven as a standalone code to compute wind turbine aerodynamic response uncoupled from FAST. When coupled to FAST, AeroDyn can also be linearized as part of the linearization of the full coupled solution (linearization is not available in standalone mode). AeroDyn was originally developed for modeling wind turbine aerodynamics, however, the module equally applies to the hydrodynamics of marine hydrokinetic (MHK) turbines (the terms “wind turbine”, “tower”, “aerodynamics” etc. in this document imply “MHK turbine”, “MHK support structure”, “hydrodynamics” etc. for MHK turbines). Additional physics important for MHK turbines, not applicable to wind turbines, computed by AeroDyn include a cavitation check. This documentation pertains to the newest release of AeroDyn—version 15 and newer, which represents a complete overhaul from earlier version of AeroDyn. AeroDyn v15 and newer follows the requirements of the FAST modularization framework.

AeroDyn calculates aerodynamic loads on both the blades and tower. Aerodynamic calculations within AeroDyn are based on the principles of actuator lines, where the three-dimensional (3D) flow around a body is approximated by local two-dimensional (2D) flow at cross sections, and the distributed pressure and shear stresses are approximated by lift forces, drag forces, and pitching moments lumped at a node in a 2D cross section. Analysis nodes are distributed along the length of each blade and tower, the 2D forces and moment at each node are computed as distributed loads per unit length, and the total 3D aerodynamic loads are found by integrating the 2D distributed loads along the length. When AeroDyn is coupled to FAST, the blade and tower analysis node discretization may be independent from the discretization of the nodes in the structural modules. The actuator line approximations restrict the validity of the model to slender structures and 3D behavior is either neglected, captured through corrections inherent in the model (e.g., tip-loss, hub-loss, or skewed-wake corrections), or captured in the input data (e.g., rotational augmentation corrections applied to airfoil data).

AeroDyn assumes the turbine geometry consists of a one-, two-, or three-bladed rotor atop a single tower. While the undeflected tower is assumed to be straight and vertical, an undeflected blade may consider out-of-plane curvature and in-plane sweep. For blades, the 2D cross sections where the aerodynamic analysis takes place may follow the out-of-plane curvature, but in-plane sweep is assumed to be accomplished by shearing, rather than rotation of the 2D cross section. Aerodynamic imbalances are possible through the use of geometrical differences between each blade.

When AeroDyn is coupled to FAST, AeroDyn receives the instantaneous (possibly displaced/deflected) structural position, orientation, and velocities of analysis nodes in the tower, hub, and blades. As with curvature and sweep, the 2D cross sections where the blade aerodynamic analysis takes place will follow the out-of-plane deflection, but in-plane deflection is assumed to be accomplished by shearing, rather than rotation of the 2D cross section. AeroDyn also receives the local freestream (undisturbed) fluid velocities at the tower and blade nodes. (Fluid and structural calculations take place outside of the AeroDyn module and are passed as inputs to AeroDyn by the driver code.) The fluid and structural motions are provided at each coupling time step and then AeroDyn computes the aerodynamic loads on the blade and

tower nodes and returns them back to FAST as part of the aero-elastic calculation. In standalone mode, the inputs to AeroDyn are prescribed by a simple driver code, without aero-elastic coupling.

AeroDyn consists of four submodels: (1) rotor wake/induction, (2) blade airfoil aerodynamics, (3) tower influence on the fluid local to the blade nodes, and (4) tower drag. Nacelle, hub, and tail-vane fluid influence and loading, aeroacoustics, and wake and array effects between multiple turbines in a wind plant, are not yet available in AeroDyn v15 and newer.

For operating wind and MHK turbine rotors, AeroDyn calculates the influence of the wake via induction factors based on the quasi-steady Blade-Element/Momentum (BEM) theory, which requires an iterative nonlinear solve (implemented via Brent's method). By quasi-steady, it is meant that the induction reacts instantaneously to loading changes. The induction calculation, and resulting inflow velocities and angles, are based on flow local to each analysis node of each blade, based on the relative velocity between the fluid and structure (including the effects of local inflow skew, shear, turbulence, tower flow disturbances, and structural motion, depending on features enabled). The Glauert's empirical correction (with Buhl's modification) replaces the linear momentum balance at high axial induction factors. In the BEM solution, Prandtl tip-loss, Prandtl hub-loss, and Pitt and Peters skewed-wake are all 3D corrections that can optionally be applied. When the skewed-wake correction is enabled, it is applied after the BEM iteration. Additionally, the calculation of tangential induction (from the angular momentum balance), the use of drag in the axial-induction calculation, and the use of drag in the tangential-induction calculation are all terms that can optionally be included in the BEM iteration (even when drag is not used in the BEM iteration, drag is still used to calculate the nodal loads once the induction has been found). The wake/induction calculation can be bypassed altogether for the purposes of modeling rotors that are parked or idling, in which case the inflow velocity and angle are determined purely geometrically. During linearization analyses with AeroDyn coupled to FAST and BEM enabled, the wake can be assumed to be frozen (i.e. the axial and tangential induces velocities, $-V_x a$ and $V_y a'$, are fixed at their operating-point values during linearization) or the induction can be recalculated during linearization using BEM theory. Dynamic wake that accounts for induction dynamics as a result of transient conditions are not yet available in AeroDyn v15 and newer.

The blade airfoil aerodynamics can be steady or unsteady, except in the case that a cavitation check is requested for MHK in which case only steady aerodynamics are supported. In the steady model, the supplied static airfoil data—including the lift-force, drag-force, and optional pitching-moment and minimum pressure coefficients versus angle of attack (AoA)—are used directly to calculate nodal loads. The [AirfoilPrep](#) preprocessor can be used to generate the needed static airfoil data based on uncorrected 2D data (based e.g. on airfoil tests in a wind tunnel or [XFOIL](#)), including features to blend data between different airfoils, apply 3D rotational augmentation, and extrapolate to high AoA. The unsteady airfoil aerodynamic (UA) models account for flow hysteresis, including unsteady attached flow, trailing-edge flow separation, dynamic stall, and flow reattachment. The UA models can be considered as 2D dynamic corrections to the static airfoil response as a result of time-varying inflow velocities and angles. Three semi-empirical UA models are available: the original theoretical developments of Beddoes-Leishman (B-L), extensions to the B-L developed by González, and extensions to the B-L model developed by

Minnema/Pierce. **While all of the UA models are documented in this manual, the original B-L model is not yet functional. Testing has shown that the González and Minnema/Pierce models produce reasonable hysteresis of the normal force, tangential force, and pitching-moment coefficients if the UA model parameters are set appropriately for a given airfoil, Reynold's number, and/or Mach number. However, the results will differ a bit from earlier versions of AeroDyn, (which was based on the Minnema/Pierce extensions to B-L) even if the default UA model parameters are used, due to differences in the UA model logic between the versions. We recommend that users run test cases with uniform wind inflow and fixed yaw error (e.g., through the standalone AeroDyn driver) to examine the accuracy of the normal force, tangential force, and pitching-moment coefficient hysteresis and to adjust the UA model parameters appropriately.** The airfoil-, Reynold's-, and Mach-dependent parameters of the UA models may be derived from the static airfoil data. These UA models are valid for small to moderate AoA under normal rotor operation; the steady model is more appropriate under parked or idling conditions. The static airfoil data is always used in the BEM iteration; when UA is enabled, it is applied after the BEM iteration and after the skewed-wake correction. The UA models are not set up to support linearization, so, UA must be disabled during linearization analyses with AeroDyn coupled to FAST. The interpolation of airfoil data based on Reynolds number or aerodynamic-control setting (e.g., flaps) is not yet available in AeroDyn v15 and newer.

The influence of the tower on the fluid flow local to the blade is based on a potential-flow and/or a tower shadow model. The potential-flow model uses the analytical potential-flow solution for flow around a cylinder to model the tower dam effect on upwind rotors. In this model, the freestream (undisturbed) flow at each blade node is disturbed based on the location of the blade node relative to the tower and the tower diameter, including lower velocities upstream and downstream of the tower, higher velocities to the left and right of the tower, and cross-stream flow. The Bak correction can optionally be included in the potential-flow model, which augments the tower upstream disturbance and improves the tower wake for downwind rotors based on the tower drag coefficient. The tower shadow model can also be enabled to account for the tower wake deficit on downwind rotors. This model includes an axial flow deficit on the freestream fluid at each blade node dependent on the location of the blade node relative to the tower and the tower diameter and drag coefficient, based on the work of Powles. Both tower-influence models are quasi-steady models, in that the disturbance is applied directly to the freestream fluid at the blade nodes without dynamics, and are applied within the BEM iteration.

The aerodynamic load on the tower is based directly on the tower diameter and drag coefficient and the local relative fluid velocity between the freestream (undisturbed) flow and structure at each tower analysis node (including the effects of local shear, turbulence, and structural motion, depending on features enabled). The tower drag load calculation is quasi-steady and independent from the tower influence on flow models.

The primary AeroDyn input file defines modeling options, environmental conditions (except freestream flow), airfoils, tower nodal discretization and properties, as well as output file specifications. Airfoil data properties are read from dedicated inputs files (one for each airfoil) and include coefficients of lift force, drag force, and optional pitching moment and minimum pressure versus AoA, as well as UA model parameters. (Minimum pressure coefficients versus AoA are also included in the airfoil input files in case that a cavitation check is requested.) Blade

nodal discretization, geometry, twist, chord, and airfoil identifier are likewise read from separate input files (one for each blade).

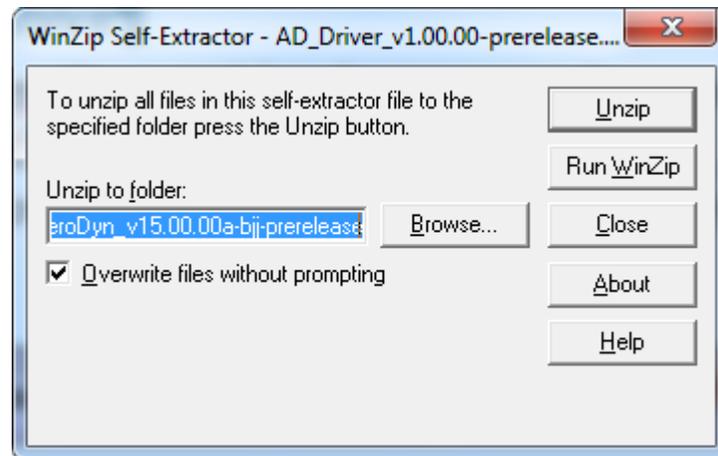
Section 3 details how to obtain the AeroDyn and FAST software archives and how to run both the standalone AeroDyn or AeroDyn coupled to FAST. Section 4 describes the AeroDyn input files. Section 5 discusses the output files generated by AeroDyn; these include an echo file, summary file, and the results file. Section 6 provides modeling guidance when using AeroDyn. The AeroDyn theory is covered in Section 7. Section 8 outlines future work, and Section 9 contains a list of references. Example input files are shown in Appendix A through D. A summary of available output channels are found in Appendix E. Appendix F tracks the major changes we have made to AeroDyn for each public release.

3 Running AeroDyn

3.1 Downloading the AeroDyn Software

3.1.1 Standalone AeroDyn Archive

You can download the standalone AeroDyn archive from our web server at <https://nwtc.nrel.gov/AeroDyn>. The file has a name similar to *AD_v15.00.00.exe*, but may have a different version number. Run the downloaded self-extracting archive (.exe) to expand the archive into a folder you specify.



The archive contains the *bin*, *CertTest*, and *Documentation* folders. The *bin* folder includes the *AeroDyn_Driver.exe*, which is used to execute the standalone AeroDyn program. The *CertTest* folder contains sample AeroDyn input files for wind and MHK applications. This manual may be found in the *Documentation* folder.

3.1.2 FAST Archive

You can download the FAST archive, which includes a coupling to AeroDyn, from our web server at <https://nwtc.nrel.gov/FAST8>. The file has a name similar to *FAST_v8.12.00.exe*, but may have a different version number. Run the downloaded self-extracting archive (.exe) to expand the archive into a folder you specify. The FAST executable is located in the archive's *bin* folder. Example models are located in the *CertTest* folder.

3.2 Running the Standalone AeroDyn

The standalone AeroDyn program, *AeroDyn_Driver.exe*, simulates aerodynamic responses of your input model, without coupling to FAST. Unlike the coupled version, the standalone software requires the use of a driver file in addition to the primary AeroDyn, airfoil, and blade input files. This driver file specifies initialization inputs normally provided to AeroDyn by FAST, as well as the per-time-step inputs to AeroDyn. Both the AeroDyn summary file and the results output file are available when using the standalone AeroDyn; see Section 5 for more information regarding the AeroDyn output files.

The AeroDyn standalone program can be run in two ways:

- 1) Run the standalone AeroDyn software from a DOS command prompt by typing, e.g.

```
>AeroDyn_Driver.exe MyDriverFile.dvr
```

where, *MyDriverFile.dvr* is the name of the AeroDyn driver file, as described in Section 4.2.

- 2) Run the standalone AeroDyn software from the MATLAB or Python scripts included in the AeroDyn archive folder. To do this, open the MATLAB or Python script and update the name of the driver file you wish you execute. The interface scripts in the samples also give examples of loading and plotting the outputs requested by the user.

The AeroDyn primary, airfoil, and blade input files are described in Sections 4.3, 4.4, and 4.5, respectively.

3.3 Running AeroDyn Coupled to FAST

Run the coupled FAST software from a DOS command prompt by typing, e.g.

```
>FAST_win32.exe Test18.fst
```

where, *Test18.fst* is the name of the primary FAST input file. This input file has a control flag to turn on or off the AeroDyn capabilities within FAST, and a corresponding reference to the primary AeroDyn input file. See the documentation supplied with FAST for further information.

4 Input Files

The user configures the aerodynamic model parameters via a primary AeroDyn input file, as well as separate input files for airfoil and blade data. When used in standalone mode, an additional driver input file is required. This driver file specifies initialization inputs normally provided to AeroDyn by FAST, as well as the per-time-step inputs to AeroDyn.

As an example, in the *CertTest* folder in the AeroDyn archive, the *XXX_driver.dvr* file is the main driver, the *XXX_input.dat* is the primary input file, the *XXX_blade.dat* file contains the blade geometry data, and the *XXX_airfoil.dat* file contains the airfoil angle of attack, lift, drag, moment coefficients, and pressure coefficients.

No lines should be added or removed from the input files, except in tables where the number of rows is specified and comment lines in the AeroDyn airfoil data files.

4.1 Units

AeroDyn uses the SI system (kg, m, s, N). Angles are assumed to be in radians unless otherwise specified.

4.2 AeroDyn Driver Input File

The driver input file is only needed for the standalone version of AeroDyn and contains inputs normally generated by FAST, and necessary to control the aerodynamic simulation for uncoupled models. A sample AeroDyn driver input file is given in Appendix A.

Set the *Echo* flag in this file to TRUE if you wish to have *AeroDyn_Driver.exe* echo the contents of the driver input file (useful for debugging errors in the driver file). The echo file has the naming convention of *OutFileRoot.ech*, where *OutFileRoot* is specified in the I/O SETTINGS section of the driver input file below. *AD_InputFile* is the filename of the primary AeroDyn input file. This name should be in quotations and can contain an absolute path or a relative path.

The TURBINE DATA section defines the AeroDyn-required turbine geometry for a rigid turbine, see Figure 1. *NumBlades* specifies the number of blades; only one-, two-, or three-bladed rotors are permitted. *HubRad* specifies the radius to the blade root from the center-of-rotation along the (possibly precone) blade-pitch axis; *HubRad* must be greater than zero. *HubHt* specifies the elevation of the hub center above the ground (or above the mean sea level (MSL) for offshore wind turbines or above the seabed for MHK turbines). *Overhang* specifies the distance along the (possibly tilted) rotor shaft between the tower centerline and hub center; *Overhang* is positive downwind, so use a negative number for upwind rotors. *ShftTilt* is the angle (in degrees) between the rotor shaft and the horizontal plane. Positive *ShftTilt* means that the downwind end of the shaft is the highest; upwind turbines have negative *ShftTilt* for improved tower clearance. *Precone* is the angle (in degrees) between a flat rotor disk and the cone swept by the blades, positive downwind; upwind turbines have negative *Precone* for improved tower clearance.

The I/O SETTINGS section controls the creation of the results file. If ***OutFileRoot*** is specified, the results file will have the filename ***OutFileRoot.#.out***, where the '#' character is an integer number corresponding to a test case line found in the COMBINED-CASE ANALYSIS section described below. If an empty string is provided for ***OutFileRoot***, then the driver file's root name will be used instead. If ***TabDel*** is TRUE, a TAB character is used between columns in the output file; if FALSE, fixed-width is used otherwise. ***OutFmt*** is any valid Fortran numeric format string, which is used for text output, excluding the time channel. The resulting field should be 10 characters, but AeroDyn does not check ***OutFmt*** for validity. If you want a sound generated on program exit, set ***Beep*** to true.

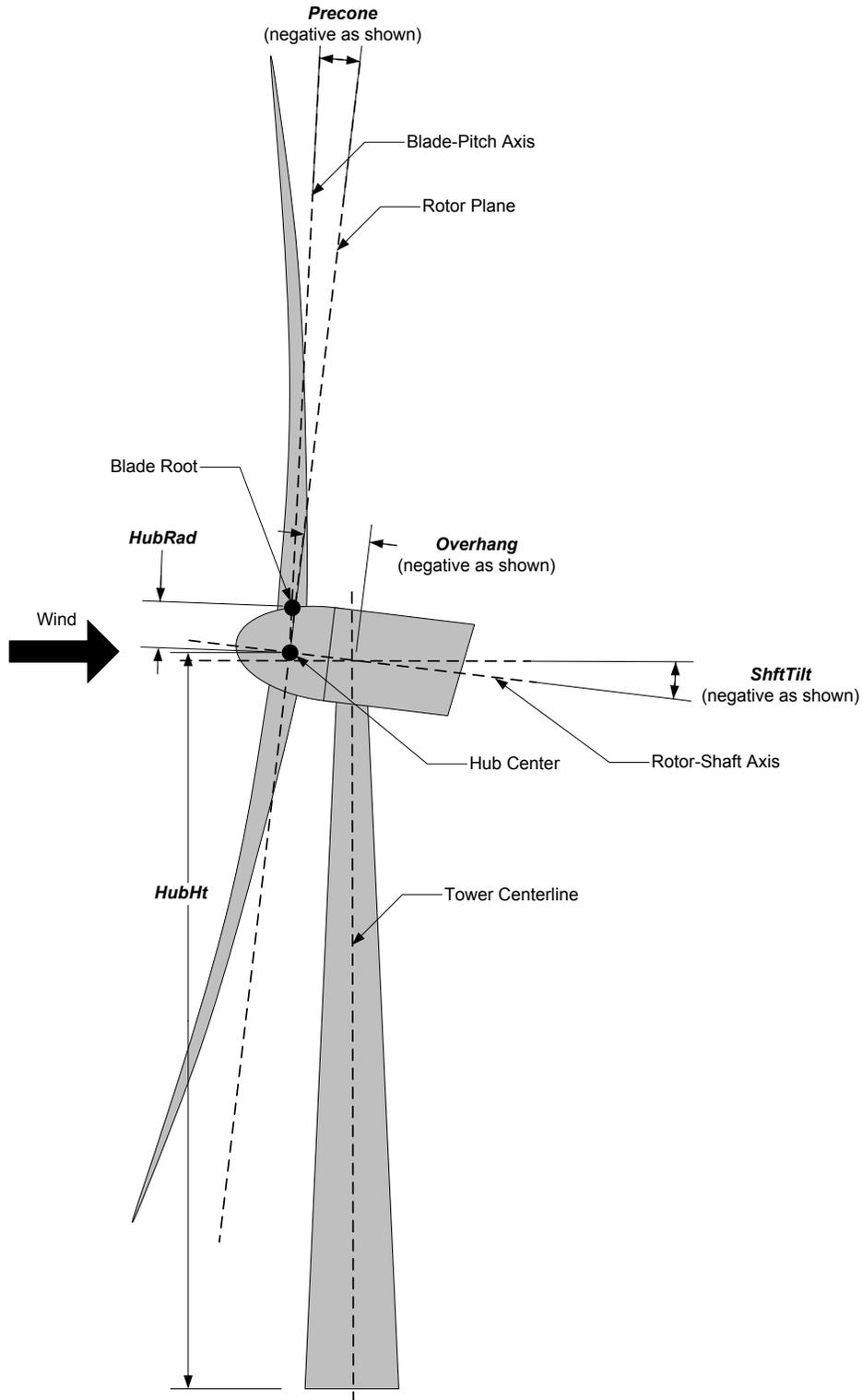


Figure 1. AeroDyn Driver Turbine Geometry

The COMBINED-CASE ANALYSIS section allows you to execute *NumCases* number of simulations for the given TURBINE DATA with a single driver input file. There will be one

row in the subsequent table for each of the *NumCases* specified (plus two table header lines). The information within each row of the table fully specifies each simulation. Each row contains the following columns: *WndSpeed*, *ShearExp*, *RotSpd*, *Pitch*, *Yaw*, *dT*, and *Tmax*. The local undisturbed wind speed for any given blade or tower node is determined using,

$$U(Z) = WndSpeed \left(\frac{Z}{HubHt} \right)^{ShearExp},$$

where *WndSpeed* is the steady wind speed (fluid flow speed in the case of an MHK turbine) located at elevation *HubHt*, *Z* is the instantaneous elevation of the blade or tower node above the ground (or above the MSL for offshore wind turbines or above the seabed for MHK turbines), and *ShearExp* is the power-law shear exponent. The fixed rotor speed (in rpm) is given by *RotSpd* (positive clockwise looking downwind), the fixed blade-pitch angle (in degrees) is given by *Pitch* (positive to feather, leading edge upwind), and the fixed nacelle-yaw angle (in degrees) is given by *Yaw* (positive rotation of the nacelle about the vertical tower axis, counterclockwise when looking downward). While the flow speed and direction in the AeroDyn driver is uniform and fixed (depending only on elevation above ground), *Yaw* and *ShftTilt* (from the TURBINE DATA section above) can introduce skewed flow. *dT* is the simulation time step, which must match the time step for the aerodynamic calculations (*DTAero*) as specified in the primary AeroDyn input file, and *Tmax* is the total simulation time.

4.3 AeroDyn Primary Input File

The primary AeroDyn input file defines modeling options, environmental conditions (except freestream flow), airfoils, tower nodal discretization and properties, as well as output file specifications.

The file is organized into several functional sections. Each section corresponds to an aspect of the aerodynamics model. A sample AeroDyn primary input file is given in Appendix B.

The input file begins with two lines of header information which is for your use, but is not used by the software.

4.3.1 General Options

Set the *Echo* flag to TRUE if you wish to have AeroDyn echo the contents of the AeroDyn primary, airfoil, and blade input files (useful for debugging errors in the input files). The echo file has the naming convention of *OutRootFile.AD.ech*. *OutRootFile* is either specified in the I/O SETTINGS section of the driver input file when running AeroDyn standalone, or by the FAST program when running a coupled simulation.

DTAero sets the time step for the aerodynamic calculations. For accuracy and numerical stability, we recommend that *DTAero* be set such that there are at least 200 azimuth steps per rotor revolution. However, when AeroDyn is coupled to FAST, FAST may require time steps much smaller than this rule of thumb. If UA is enabled while using very small time steps, you may need to recompile AeroDyn in double precision to avoid numerical problems in the UA routines. The keyword 'DEFAULT' for *DTAero* may be used to indicate that AeroDyn should employ the time step prescribed by the driver code (FAST or the standalone driver program).

Set *WakeMod* to 0 if you want to disable rotor wake/induction effects or 1 to include these effects using the BEM theory model. Set *AFAeroMod* to 1 to include steady blade airfoil aerodynamics or 2 to enable UA; *AFAeroMod* must be 1 during linearization analyses with AeroDyn coupled to FAST. Set *TwrPotent* to 0 to disable the potential-flow influence of the tower on the fluid flow local to the blade, 1 to enable the standard potential-flow model, or 2 to include the Bak correction in the potential-flow model. Set the *TwrShadow* flag to TRUE to include the influence of the tower on the flow local to the blade based on the downstream tower shadow model or FALSE to disable these effects. If the tower influence from potential flow and tower shadow are both enabled, the two influences will be superimposed. Set the *TwrAero* flag to TRUE to calculate fluid drag loads on the tower or FALSE to disable these effects. During linearization analyses with AeroDyn coupled FAST and BEM enabled (*WakeMod* = 1), set the *FrozenWake* flag to TRUE to employ frozen-wake assumptions during linearization (i.e. to fix the axial and tangential induced velocities, $-V_x a$ and $V_y a'$, at their operating-point values during linearization) or FALSE to recalculate the induction during linearization using BEM theory. Set the *CavitCheck* flag to TRUE to perform a cavitation check for MHK turbines or FALSE to disable this calculation. If *CavitCheck* is TRUE, *AFAeroMod* must be set to 1 because the cavitation check does not function with unsteady airfoil aerodynamics.

4.3.2 Environmental Conditions

AirDens specifies the fluid density and must be a value greater than zero; a typical value is around 1.225 kg/m³ for air (wind turbines) and 1025 kg/m³ for seawater (MHK turbines). *KinVisc* specifies the kinematic viscosity of the air (used in the Reynolds number calculation); a typical value is around 1.460E-5 m²/s for air (wind turbines) and 1.004E-6 m²/s for seawater (MHK turbines). *SpdSound* is the speed of sound in air (used to calculate the Mach number within the unsteady airfoil aerodynamics calculations); a typical value is around 340.3 m/s. The last three parameters in this section are only used when *CavitCheck* = TRUE for MHK turbines. *Patm* is the atmospheric pressure above the free surface; typically around 101,325 Pa. *Pvap* is the vapor pressure of the fluid; for seawater this is typically around 2,000 Pa. *FluidDepth* is the distance from the hub center to the free surface.

4.3.3 Blade-Element/Momentum Theory

The input parameters in this section are only used when *WakeMod* = 1.

SkewMod determines the skewed-wake correction model. Set *SkewMod* to 1 to use the uncoupled BEM solution technique without an additional skewed-wake correction. Set *SkewMod* to 2 to include the Pitt/Peters correction model. **The coupled model (*SkewMod* = 3) is not available in this version of AeroDyn.**

Set *TipLoss* to TRUE to include the Prandtl tip-loss model or FALSE to disable it. Likewise, set *HubLoss* to TRUE to include the Prandtl hub-loss model or FALSE to disable it.

Set *TanInd* to TRUE to include tangential induction (from the angular momentum balance) in the BEM solution or FALSE to neglect it. Set *AIDrag* to TRUE to include drag in the axial-induction calculation or FALSE to neglect it. If *TanInd* = TRUE, set *TIDrag* to TRUE to include drag in the tangential-induction calculation or FALSE to neglect it. Even when drag is

not used in the BEM iteration, drag is still used to calculate the nodal loads once the induction has been found,

IndToler sets the convergence threshold for the iterative nonlinear solve of the BEM solution. The nonlinear solve is in terms of the inflow angle, but *IndToler* represents the tolerance of the nondimensional residual equation, with no physical association possible. When the keyword ‘DEFAULT’ is used in place of a numerical value, *IndToler* will be set to 5E-5 when AeroDyn is compiled in single precision and to 5E-10 when AeroDyn is compiled in double precision; we recommend using these defaults. *MaxIter* determines the maximum number of iterations steps in the BEM solve. If the residual value of the BEM solve is not less than or equal to *IndToler* in *MaxIter*, AeroDyn will exit the BEM solver and return an error message.

4.3.4 Unsteady Airfoil Aerodynamics Options

The input parameters in this section are only used when *AFAeroMod* = 2.

UAMod determines the UA model. Setting *UAMod* to 1 enables original theoretical developments of B-L, 2 enables the extensions to B-L developed by González, and 3 enables the extensions to B-L developed by Minnema/Pierce. **While all of the UA models are documented in this manual, the original B-L model is not yet functional. Testing has shown that the González and Minnema/Pierce models produce reasonable hysteresis of the normal force, tangential force, and pitching-moment coefficients if the UA model parameters are set appropriately for a given airfoil, Reynold’s number, and/or Mach number. However, the results will differ a bit from earlier versions of AeroDyn, (which was based on the Minnema/Pierce extensions to B-L) even if the default UA model parameters are used, due to differences in the UA model logic between the versions. We recommend that users run test cases with uniform inflow and fixed yaw error (e.g., through the standalone AeroDyn driver) to examine the accuracy of the normal force, tangential force, and pitching-moment coefficient hysteresis and to adjust the UA model parameters appropriately.**

FLookup determines how the nondimensional separation distance value, f' , will be calculated. When *FLookup* is set to TRUE, f' is determined via a lookup into the static lift-force coefficient and drag-force coefficient data. **Using best-fit exponential equations (*FLookup* = FALSE) is not yet available, so *FLookup* must be TRUE in this version of AeroDyn.**

4.3.5 Airfoil Information

This section defines the airfoil data input file information. The airfoil data input files themselves (one for each airfoil) include tables containing coefficients of lift force, drag force, and optionally pitching moment, and minimum pressure versus AoA, as well as UA model parameters, and are described in Section 4.4.

The first 5 lines in the AIRFOIL INFORMATION section relate to the format of the tables of static airfoil coefficients within each of the airfoil input files. *InCol_Alfa*, *InCol_Cl*, *InCol_Cd*, *InCol_Cm*, and *InCol_Cpmin* are column numbers in the tables containing the AoA, lift-force coefficient, drag-force coefficient, pitching-moment coefficient, and minimum pressure coefficient, respectively (normally these are 1, 2, 3, 4, and 5, respectively). If pitching-moment terms are neglected with *UseBlCm* = FALSE, *InCol_Cm* may be set to zero, and if the cavitation check is disabled with *CavitCheck* = FALSE, *InCol_Cpmin* may be set to zero.

Specify the number of airfoil data input files to be used using *NumAFfiles*, followed by *NumAFfiles* lines of filenames. The file names should be in quotations and can contain an absolute path or a relative path e.g., “C:\airfoils\S809_CLN_298.dat” or “airfoils\S809_CLN_298.dat”. If you use relative paths, it is relative to the location of the current working directory. The blade data input files will reference these airfoil data using their line identifier, where the first airfoil file is numbered 1 and the last airfoil file is numbered *NumAFfiles*.

4.3.6 Rotor/Blade Properties

Set *UseBICm* to TRUE to include pitching-moment terms in the blade airfoil aerodynamics or FALSE to neglect them; if *UseBICm* = TRUE, pitching-moment coefficient data must be included in the airfoil data tables with *InCol_Cm* not equal to zero.

The blade nodal discretization, geometry, twist, chord, and airfoil identifier are set in separate input files for each blade, described in Section 4.5. *ADBIFile(1)* is the filename for blade 1, *ADBIFile(2)* is the filename for blade 2, and *ADBIFile(3)* is the filename for blade 3, respectively; the latter is not used for two-bladed rotors and the latter two are not used for one-bladed rotors. The file names should be in quotations and can contain an absolute path or a relative path. The data in each file need not be identical, which permits modeling of aerodynamic imbalances.

4.3.7 Tower Influence and Aerodynamics

The input parameters in this section pertain to the tower influence and/or tower drag calculations and are only used when *TwrPotent* > 0, *TwrShadow* = TRUE, or *TwrAero* = TRUE.

NumTwrNds is the user-specified number of tower analysis nodes and determines the number of rows in the subsequent table (after two table header lines). *NumTwrNds* must be greater than or equal to two; the higher the number, the finer the resolution and longer the computational time; we recommend that *NumTwrNds* be between 10 and 20 to balance accuracy with computational expense. For each node, *TwrElev* specifies the local elevation of the tower node above ground (or above MSL for offshore wind turbines or above the seabed for MHK turbines), *TwrDiam* specifies the local tower diameter, and *TwrCd* specifies the local tower drag-force coefficient. *TwrElev* must be entered in monotonically increasing order—from the lowest (tower-base) to the highest (tower-top) elevation. See Figure 2.

4.3.8 Outputs

Specifying *SumPrint* to TRUE causes AeroDyn to generate a summary file with name *OutFileRoot.AD.sum*. *OutFileRoot* is either specified in the I/O SETTINGS section of the driver input file when running AeroDyn standalone, or by the FAST program when running a coupled simulation. See section 5.2 for summary file details.

AeroDyn can output aerodynamic and kinematic quantities at up to nine nodes along the tower and up to nine nodes along each blade. *NBIOuts* specifies the number of blade nodes that output is requested for (0 to 9) and *BIOutNd* on the next line is a list *NBIOuts* long of node numbers between 1 and *NumBINds* (corresponding to a row number in the blade analysis node table in the blade data input files), separated by any combination of commas, semicolons, spaces, and/or tabs. All blades have the same output node numbers. *NTwOuts* specifies the number of tower

nodes that output is requested for (0 to 9) and *TwOutNd* on the next line is a list *NTwOuts* long of node numbers between 1 and *NumTwrNds* (corresponding to a row number in the tower analysis node table above), separated by any combination of commas, semicolons, spaces, and/or tabs. The outputs specified in the *OutList* section determine which quantities are actually output at these nodes.

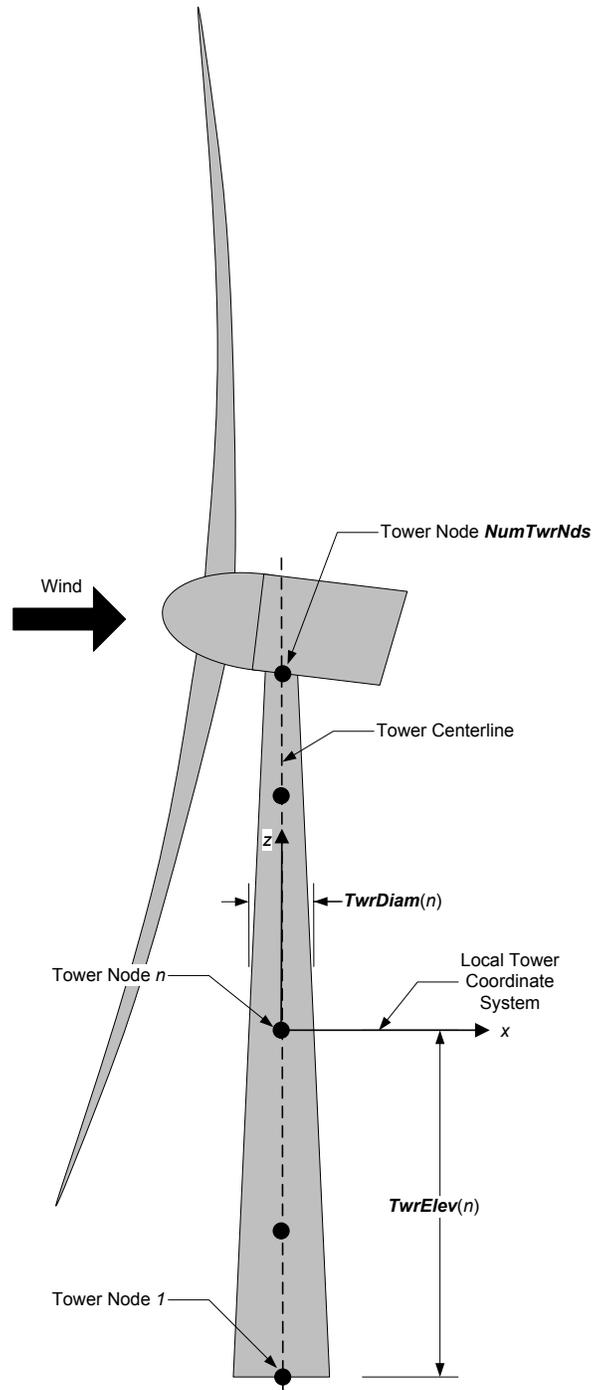


Figure 2. AeroDyn Tower Geometry

The **OutList** section controls output quantities generated by AeroDyn. Enter one or more lines containing quoted strings that in turn contain one or more output parameter names. Separate output parameter names by any combination of commas, semicolons, spaces, and/or tabs. If you prefix a parameter name with a minus sign, “-”, underscore, “_”, or the characters “m” or “M”, AeroDyn will multiply the value for that channel by -1 before writing the data. The parameters are written in the order they are listed in the input file. AeroDyn allows you to use multiple lines so that you can break your list into meaningful groups and so the lines can be shorter. You may enter comments after the closing quote on any of the lines. Entering a line with the string “END” at the beginning of the line or at the beginning of a quoted string found at the beginning of the line will cause AeroDyn to quit scanning for more lines of channel names. Blade and tower node-related quantities are generated for the requested nodes identified through the **BlOutNd** and **TwOutNd** lists above. If AeroDyn encounters an unknown/invalid channel name, it warns the users but will remove the suspect channel from the output file. Please refer to Appendix E for a complete list of possible output parameters.

4.4 Airfoil Data Input File

The airfoil data input files themselves (one for each airfoil) include tables containing coefficients of lift force, drag force, and pitching moment versus AoA, as well as UA model parameters. In these files, any line whose first non-blank character is an exclamation point (!) is ignored (for inserting comment lines). The non-comment lines should appear within the file in order, but comment lines may be intermixed as desired for reading clarity. A sample airfoil data input file is given in Appendix C.

InterpOrd is the order the static airfoil data is interpolated when AeroDyn uses table look-up to find the lift-, drag-, and optional pitching-moment, and minimum pressure coefficients as a function of AoA. When **InterpOrd** is 1, linear interpolation is used; when **InterpOrd** is 3, the data will be interpolated with cubic splines; if the keyword ‘DEFAULT’ is entered in place of a numerical value, **InterpOrd** is set to 3.

NonDimArea is the nondimensional airfoil area (normalized by the local **BlChord** squared), but is currently unused by AeroDyn. **NumCoords** is the number of points to define the exterior shape of the airfoil, plus one point to define the aerodynamic center, and determines the number of rows in the subsequent table; **NumCoords** must be exactly zero or greater than or equal to three. For each point, the nondimensional *X* and *Y* coordinates are specified in the table, **X_Coord** and **Y_Coord** (normalized by the local **BlChord**). The first point must always locate the aerodynamic center (reference point for the airfoil lift and drag forces, likely not on the surface of the airfoil); the remaining points should define the exterior shape of the airfoil. The airfoil shape is currently unused by AeroDyn, but when AeroDyn is coupled to FAST, the airfoil shape will be used by FAST for blade surface visualization when enabled.

Specify the number of Reynold’s number- or aerodynamic-control setting-dependent tables of data for the given airfoil via the **NumTabs** setting. **Currently, AeroDyn can only use the first table in any given airfoil file, so you should set $NumTabs = 1$ and you will need to make separate airfoil data input files and run separate simulations if you need to analyze data for**

different Reynold's numbers or aerodynamic-control settings. The remaining parameters in the airfoil data input files are entered separately for each table.

Re and *Ctrl* are the Reynold's number (in millions) and aerodynamic-control setting for the included table, **but are both currently unused by AeroDyn.**

Set *InclUAdata* to TRUE if you are including the 32 UA model parameters (required when *AFAeroMod* = 2 in the AeroDyn primary input file):

- *alpha0* specifies the zero-lift AoA (in degrees);
- *alpha1* specifies the AoA (in degrees) larger than *alpha0* for which *f* equals 0.7; approximately the positive stall angle;
- *alpha2* specifies the AoA (in degrees) less than *alpha0* for which *f* equals 0.7; approximately the negative stall angle;
- *eta_e* is the recovery factor and typically has a value in the range [0.85 to 0.95] for *UAMod* = 1; if the keyword 'DEFAULT' is entered in place of a numerical value, *eta_e* is set to 0.9 for *UAMod* = 1, but *eta_e* is set to 1.0 for other *UAMod* values and whenever *FLookup* = TRUE;
- *C_nalpha* is the slope of the 2D normal force coefficient curve in the linear region;
- *T_f0* is the initial value of the time constant associated with *Df* in the expressions of *Df* and *f*'; if the keyword 'DEFAULT' is entered in place of a numerical value, *T_f0* is set to 3.0;
- *T_V0* is the initial value of the time constant associated with the vortex lift decay process, used in the expression of *Cvn*; it depends on Reynold's number, Mach number, and airfoil; if the keyword 'DEFAULT' is entered in place of a numerical value, *T_V0* is set to 6.0;
- *T_p* is the boundary-layer leading edge pressure gradient time constant in the expression for *Dp* and should be tuned based on airfoil experimental data; if the keyword 'DEFAULT' is entered in place of a numerical value, *T_p* is set to 1.7;
- *T_VL* is the time constant associated with the vortex advection process, representing the nondimensional time in semi-chords needed for a vortex to travel from the leading to trailing edges, and used in the expression of *Cvn*; it depends on Reynold's number, Mach number (weakly), and airfoil; valued values are in the range [6 to 13]; if the keyword 'DEFAULT' is entered in place of a numerical value, *T_VL* is set to 11.0;
- *b1* is a constant in the expression of ϕ_α^c and ϕ_q^c ; this value is relatively insensitive for thin airfoils, but may be different for turbine airfoils; if the keyword 'DEFAULT' is entered in place of a numerical value, *b1* is set to 0.14, based on experimental results;

- **b2** is a constant in the expression of ϕ_α^c and ϕ_q^c ; this value is relatively insensitive for thin airfoils, but may be different for turbine airfoils; if the keyword 'DEFAULT' is entered in place of a numerical value, **b2** is set to 0.53, based on experimental results;
- **b5** is a constant in the expression of K_q^m , Cm_q^{nc} , and k_{m_q} ; if the keyword 'DEFAULT' is entered in place of a numerical value, **b5** is set to 5, based on experimental results;
- **A1** is a constant in the expression of ϕ_α^c and ϕ_q^c ; this value is relatively insensitive for thin airfoils, but may be different for turbine airfoils; if the keyword 'DEFAULT' is entered in place of a numerical value, **A1** is set to 0.3, based on experimental results;
- **A2** is a constant in the expression of ϕ_α^c and ϕ_q^c ; this value is relatively insensitive for thin airfoils, but may be different for turbine airfoils; if the keyword 'DEFAULT' is entered in place of a numerical value, **A2** is set to 0.7, based on experimental results;
- **A5** is a constant in the expression of K_q^m , Cm_q^{nc} , and k_{m_q} ; if the keyword 'DEFAULT' is entered in place of a numerical value, **A5** is set to 1, based on experimental results;
- **S1** is the constant in the best fit curve of f for $\alpha0 \leq \text{AoA} \leq \alpha1$ for $UAMod = 1$ (and is unused otherwise); by definition, it depends on the airfoil;
- **S2** is the constant in the best fit curve of f for $\text{AoA} > \alpha1$ for $UAMod = 1$ (and is unused otherwise); by definition, it depends on the airfoil;
- **S3** is the constant in the best fit curve of f for $\alpha2 \leq \text{AoA} \leq \alpha0$ for $UAMod = 1$ (and is unused otherwise); by definition, it depends on the airfoil;
- **S4** is the constant in the best fit curve of f for $\text{AoA} < \alpha2$ for $UAMod = 1$ (and is unused otherwise); by definition, it depends on the airfoil;
- **Cn1** is the critical value of C_n^i at leading-edge separation for positive AoA and should be extracted from airfoil data at a given Reynold's number and Mach number; **Cn1** can be calculated from the static value of C_n at either the break in the pitching moment or the loss of chord force at the onset of stall; **Cn1** is close to the condition of maximum lift of the airfoil at low Mach numbers;
- **Cn2** is the critical value of C_n^i at leading-edge separation for negative AoA and should be extracted from airfoil data at a given Reynold's number and Mach number; **Cn2** can be calculated from the static value of C_n at either the break in the pitching moment or the loss of chord force at the onset of stall; **Cn2** is close to the condition of maximum lift of the airfoil at low Mach numbers;

- ***St_sh*** is the Strouhal's shedding frequency; if the keyword 'DEFAULT' is entered in place of a numerical value, ***St_sh*** is set to 0.19;
- ***Cd0*** is the drag-force coefficient at zero-lift AoA;
- ***Cm0*** is the pitching-moment coefficient about the quarter-chord location at zero-lift AoA, positive for nose up;
- ***k0*** is a constant in the best fit curve of \hat{x}_{cp} and equals $\hat{x}_{AC} - 0.25$ for ***UAMod*** = 1 (and is unused otherwise);
- ***k1*** is a constant in the best fit curve of \hat{x}_{cp} for ***UAMod*** = 1 (and is unused otherwise);
- ***k2*** is a constant in the best fit curve of \hat{x}_{cp} for ***UAMod*** = 1 (and is unused otherwise);
- ***k3*** is a constant in the best fit curve of \hat{x}_{cp} for ***UAMod*** = 1 (and is unused otherwise);
- ***k1_hat*** is a constant in the expression of *Cc* due to leading-edge vortex effects for ***UAMod*** = 1 (and is unused otherwise);
- ***x_cp_bar*** is a constant in the expression of \hat{x}_{cp}^v for ***UAMod*** = 1 (and is unused otherwise); if the keyword 'DEFAULT' is entered in place of a numerical value, ***x_cp_bar*** is set to 0.2; and
- ***UACutOut*** is the AoA (in degrees) in absolute value above which UA are disabled; if the keyword 'DEFAULT' is entered in place of a numerical value, ***UACutOut*** is set to 45.
- ***filtCutOff*** is the cut-off frequency (-3 dB corner frequency) (in Hz) of the low-pass filter applied to the AoA input to UA, as well as to the pitch rate and pitch acceleration derived from AoA within UA; if the keyword 'DEFAULT' is entered in place of a numerical value, ***filtCutOff*** is set to 20.

NumAlf is the number of distinct AoA entries and determines the number of rows in the subsequent table of static airfoil coefficients; ***NumAlf*** must be greater than or equal to one (***NumAlf*** = 1 implies constant coefficients, regardless of the AoA). AeroDyn will interpolate the data provided via linear interpolation or via cubic splines, depending on the setting of input ***InterpOrd*** above. For each AoA, you must set the AoA (in degrees), ***alpha***, the lift-force coefficient, ***Coefs(:,1)***, the drag-force coefficient, ***Coefs(:,2)***, and optionally the pitching-moment coefficient, ***Coefs(:,3)***, and minimum pressure coefficient, ***Coefs(:,4)***, but the column order depends on the settings of ***InCol_Alfa***, ***InCol_Cl***, ***InCol_Cd***, ***InCol_Cm***, and ***InCol_Cpmin*** in the AIRFOIL INFORMATION section of the AeroDyn primary input file. AoA must be entered in monotonically increasing order—from lowest to highest AoA—and the first row should be for AoA = -180 and the last should be for AoA = +180 (unless ***NumAlf*** = 1, in which case AoA is unused). If pitching-moment terms are neglected with ***UseBICm*** = FALSE in the

ROTOR/BLADE PROPERTIES section of the AeroDyn primary input file, the column containing pitching-moment coefficients may be absent from the file. Likewise, if the cavitation check is neglected with *CavitCheck* = FALSE in the GENERAL OPTIONS section of the AeroDyn primary input file, the column containing the minimum pressure coefficients may be absent from the file.

4.5 Blade Data Input File

The blade data input file contains the nodal discretization, geometry, twist, chord, and airfoil identifier for a blade. Separate files are used for each blade, which permits modeling of aerodynamic imbalances. A sample blade data input file is given in Appendix D.

The input file begins with two lines of header information which is for your use, but is not used by the software.

NumBLNds is the user-specified number of blade analysis nodes and determines the number of rows in the subsequent table (after two table header lines). *NumBLNds* must be greater than or equal to two; the higher the number, the finer the resolution and longer the computational time; we recommend that *NumBLNds* be between 10 and 20 to balance accuracy with computational expense. Even though *NumBLNds* is defined in each blade file, all blades must have the same number of nodes. For each node:

- *BlSpn* specifies the local span of the blade node along the (possibly precone) blade-pitch axis from the root; *BlSpn* must be entered in monotonically increasing order—from the most inboard to the most outboard—and the first node must be zero, and when AeroDyn is coupled to FAST, the last node should be located at the blade tip;
- *BlCrvAC* specifies the local out-of-plane offset (when the blade-pitch angle is zero) of the aerodynamic center (reference point for the airfoil lift and drag forces), normal to the blade-pitch axis, as a result of blade curvature; *BlCrvAC* is positive downwind; upwind turbines have negative *BlCrvAC* for improved tower clearance;
- *BlSwpAC* specifies the local in-plane offset (when the blade-pitch angle is zero) of the aerodynamic center (reference point for the airfoil lift and drag forces), normal to the blade-pitch axis, as a result of blade sweep; positive *BlSwpAC* is opposite the direction of rotation;
- *BlCrvAng* specifies the local angle (in degrees) from the blade-pitch axis of a vector normal to the plane of the airfoil, as a result of blade out-of-plane curvature (when the blade-pitch angle is zero); *BlCrvAng* is positive downwind; upwind turbines have negative *BlCrvAng* for improved tower clearance;
- *BlTwist* specifies the local aerodynamic twist angle (in degrees) of the airfoil; it is the orientation of the local chord about the vector normal to the plane of the airfoil, positive to feather, leading edge upwind; the blade-pitch angle will be added to the local twist;
- *BlChord* specifies the local chord length; and

- BLAFID** specifies which airfoil data the local blade node is associated with; valid values are numbers between 1 and **NumAFfiles** (corresponding to a row number in the airfoil file table in the AeroDyn primary input file); multiple blade nodes can use the same airfoil data.

See Figure 3. Twist is shown in Figure 4 of Appendix E.

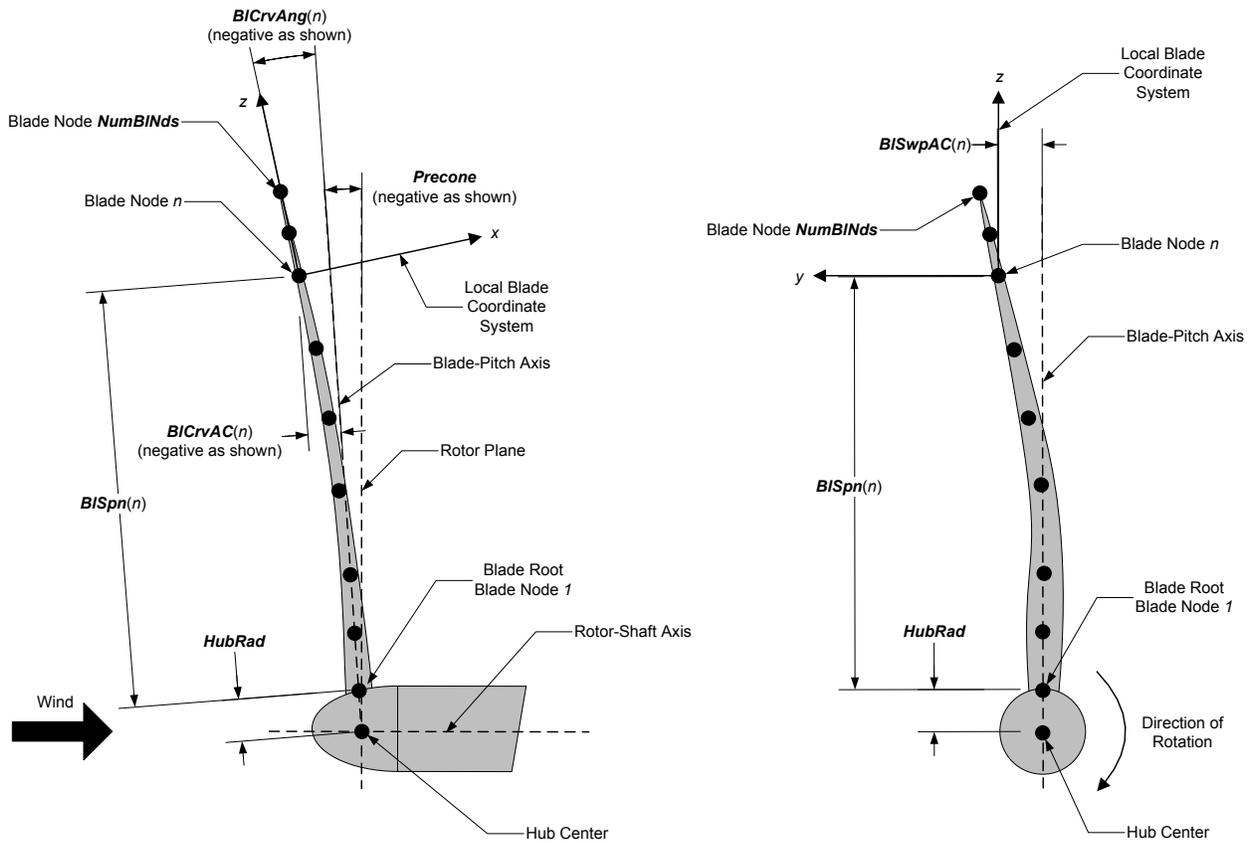


Figure 3. AeroDyn Blade Geometry – Left: Side View; Right: Front View (Looking Downwind)

5 Output Files

AeroDyn produces three types of output files: an echo file, a summary file, and a time-series results file. The following sections detail the purpose and contents of these files.

5.1 Echo Files

If you set the *Echo* flag to TRUE in the AeroDyn driver file or the AeroDyn primary input file, the contents of those files will be echoed to a file with the naming conventions, *OutFileRoot.ech* for the driver input file and *OutFileRoot.AD.ech* for the AeroDyn primary input file. *OutFileRoot* is either specified in the I/O SETTINGS section of the driver input file when running AeroDyn standalone, or by the FAST program when running a coupled simulation. The echo files are helpful for debugging your input files. The contents of an echo file will be truncated if AeroDyn encounters an error while parsing an input file. The error usually corresponds to the line after the last successfully echoed line.

5.2 Summary File

AeroDyn generates a summary file with the naming convention, *OutFileRoot.AD.sum* if the *SumPrint* parameter is set to TRUE. *OutFileRoot* is either specified in the I/O SETTINGS section of the driver input file when running AeroDyn standalone, or by the FAST program when running a coupled simulation. This file summarizes key information about your aerodynamics model, including which features have been enabled and what outputs have been selected.

5.3 Results Files

In standalone mode, the AeroDyn time-series results (a separate file for each case) are written to text-based files with the naming convention *OutFileRoot.#.out*, where *OutFileRoot* is specified in the I/O SETTINGS section of the driver input file and the '#' character is an integer number corresponding to a test case line found in the COMBINED-CASE ANALYSIS section. If AeroDyn is coupled to FAST, then FAST will generate a master results file that includes the AeroDyn results and AeroDyn will not write out its own results. The results are in table format, where each column is a data channel (the first column always being the simulation time), and each row corresponds to a simulation output time step. The data channels are specified in the OUTPUTS section of the AeroDyn primary input file. The column format of the AeroDyn-generated files is specified using the *OutFmt* parameter of the driver input file.

6 Modeling Considerations

AeroDyn was designed as an extremely flexible tool for modeling a wide-range of aerodynamic conditions and turbine configurations. This section provides some general guidance to help you construct models that are compatible with AeroDyn.

Please refer to the theory of Section 7 for detailed information about the implementation approach we have followed in AeroDyn.

6.1 Standalone AeroDyn Driver

The standalone AeroDyn driver code is very useful for computing turbine aerodynamics independent of aero-elastic coupling. The standalone AeroDyn driver code essentially replaces the functionality previously available in the separate wind turbine rotor-performance tool WT_Perf. For example, the standalone AeroDyn driver code can be used to compute the surfaces of power coefficient (C_p), thrust coefficient (C_T), and/or torque coefficient (C_Q) as a function of tip-speed ratio (TSR) and blade-pitch angle for a given rotor. Moreover, the standalone AeroDyn driver code is more powerful than WT_Perf in that the standalone AeroDyn driver can capture time-varying dynamics as a result of nacelle-yaw error, shaft tilt, and/or wind shear.

6.2 Environmental Conditions

For air, typical values for *AirDens*, *KinVisc*, *SpdSound*, and *Patm* are around 1.225 kg/m³, 1.460E-5 m²/s, 340.3 m/s, and 101,325 Pa, respectively. For seawater, typical values for *AirDens*, *KinVisc*, and *Pvap* are around 1025 kg/m³, 1.004E-6 m²/s, and 2000 Pa, respectively.

6.3 Temporal and Spatial Discretization

For accuracy and numerical stability, we recommend that *DTAero* be set such that there are at least 200 azimuth steps per rotor revolution. However, when AeroDyn is coupled to FAST, FAST may require time steps much smaller than this rule of thumb. If UA is enabled while using very small time steps, you may need to recompile AeroDyn in double precision to avoid numerical problems in the UA routines.

For the blade and tower spatial discretization, using higher number of analysis nodes will result in a more accurate solution at the expense of longer computational time. When AeroDyn is coupled to FAST, the blade and tower analysis node discretization may be independent from the discretization of the nodes in the structural modules.

We recommend that *NumBlNds* be between 10 and 20 to balance accuracy with computational expense for the rotor aerodynamic load calculation. It may be beneficial to use a finer resolution of nodes where large gradients are expected in the aerodynamic loads e.g. near the blade tip. Aerodynamic imbalances are possible through the use of geometrical differences between each blade.

When the tower potential-flow (*TwrPotent* > 0), tower shadow (*TwrShadow* = TRUE), and/or the tower aerodynamic load (*TwrAero* = TRUE) models are enabled, we also recommend that *NumTwrNds* be between 10 and 20 to balance accuracy with computational expense. Normally the local elevation of the tower node above ground (or above MSL for offshore wind turbines or

above the seabed for MHK turbines) (*TwrElev*), must be entered in monotonically increasing order from the lowest (tower-base) to the highest (tower-top) elevation. However, when AeroDyn is coupled to FAST, the tower-base node in AeroDyn cannot be set lower than the lowest point where wind is specified in the InflowWind module. To avoid truncating the lower section of the tower in AeroDyn, we recommend that the wind be specified in InflowWind as low to the ground (or MSL for offshore wind turbines or above the seabed for MHK turbines) as possible (this is a particular issue for full-field wind file formats).

6.4 Model Options Under Operational and Parked/Idling Conditions

To model an operational rotor, we recommend to include induction (*WakeMod* = 1) and UA (*AFAeroMod* = 2). Normally, the Pitt and Peters skewed-wake (*SkewMod* = 2), Prandtl tip-loss (*TipLoss* = TRUE), Prandtl hub-loss (*HubLoss* = TRUE), and tangential induction (*TanInd* = TRUE) models should all be enabled, but *SkewMod* = 2 is invalid for very large yaw errors (much greater than 45°). The nonlinear solve in the BEM solution is in terms of the inflow angle, but *IndToler* represents the tolerance of the nondimensional residual equation, with no physical association possible; we recommend setting *IndToler* to 'DEFAULT'.

While all of the UA models are documented in this manual, the original B-L model is not yet functional. Testing has shown that the González and Minnema/Pierce models produce reasonable hysteresis of the normal force, tangential force, and pitching-moment coefficients if the UA model parameters are set appropriately for a given airfoil, Reynold's number, and/or Mach number. However, the results will differ a bit from earlier versions of AeroDyn, (which was based on the Minnema/Pierce extensions to B-L) even if the default UA model parameters are used, due to differences in the UA model logic between the versions. We recommend that users run test cases with uniform inflow and fixed yaw error (e.g., through the standalone AeroDyn driver) to examine the accuracy of the normal force, tangential force, and pitching-moment coefficient hysteresis and to adjust the UA model parameters appropriately.

To model a parked or idling rotor, we recommend to disable induction (*WakeMod* = 0) and UA (*AFAeroMod* = 1), in which case the inflow velocity and angle are determined purely geometrically and the airfoil data is determined statically.

The direct aerodynamic load on the tower often dominates the aerodynamic load on the rotor for parked or idling conditions above the cut-out wind speed, in which case we recommend that *TwrAero* = TRUE. Otherwise, *TwrAero* = FALSE may be satisfactory.

We recommend to include the influence of the tower on the fluid local to the blade for both operational and parked/idling rotors. We recommend that *TwrPotent* > 0 for upwind rotors and that *TwrPotent* = 2 or *TwrShadow* = TRUE for downwind rotors.

6.5 Linearization

When coupled to FAST, AeroDyn can be linearized as part of the linearization of the full coupled solution. When induction is enabled (*WakeMod* = 1), we recommend to base the linearized solution on the frozen-wake assumption, by setting *FrozenWake* = TRUE. The UA

models are not set up to support linearization, so, UA must be disabled during linearization by setting *AF AeroMod* = 1.

7 AeroDyn Theory

Future versions of the manual will include documentation of the theory behind AeroDyn.

8 Future Work

This list contains features that could be implemented in future releases:

- Correct convergence issues where the BEM algorithm throws an error regarding “no valid value of phi” e.g. near $V_x = 0$.
- Enable the coupled skewed-wake correction model (*SkewMod* = 3).
- Add dynamic wake based on time-filtered BEM
- Add dynamic wake based on GDW.
- Add a free-wake vortex method.
- Enable the UA model based on the original theoretical developments of B-L (*UAMod* = 1).
- Enable the best-fit exponential equations for the nondimensional separation distance in UA (*FLookup* = FALSE).
- Add additional UA models e.g. Galbraith et al, Munduate et al, ONERA.
- Add UA models for active flow-control devices.
- Enable interpolation of airfoil data based on Reynold’s number and aerodynamic-control setting (*NumTabs* > 1).
- Add nacelle, hub, and tail-vane wind influence and loading.
- Use airfoil tables to calculate tower, nacelle, and hub loading.
- Add an interface to the [Dynamic Wake Meandering \(DWM\) model](#).
- Add additional hub- and tip-loss corrections to BEM e.g. Goldstein, Shen et al.
- Add coned rotor corrections to BEM e.g. Mikkelsen, Crawford.
- Develop improved empirically and high-fidelity modeling-derived corrections to engineering models (e.g. hub and tip loss, stall delay, curved blades, highly coned rotors, winglets).
- Support linearization of UA.
- Automate rotational augmentation calculation (as an alternative to [AirfoilPrep](#)).
- Allow distinct input and analysis nodes with automated interpolation of airfoil data between them.
- Add aeroacoustics (noise).
- Implement new physics for MHK turbines, including added mass and buoyancy.
- Support vertical-axis wind turbines.

9 References

Future versions of the manual will include references pertinent to AeroDyn.

Appendix A. Example AeroDyn v15.04.* Driver Input File

```
----- AeroDyn Driver v1.00.x Input File -----
UAE Phase 3 turbine (BEM)
----- Input Configuration -----
True      Echo          - Echo input parameters to "<rootname>.ech"?
"Test01_UAE_AeroDyn.dat" AD_InputFile - Name of the primary AeroDyn input file
----- Turbine Data -----
      2  NumBlades      - Number of blades (-)
      0.432 HubRad      - Hub radius (m)
      12.192 HubHt      - Hub height (m)
      0  Overhang       - Overhang (m)
      0  ShftTilt       - Shaft tilt (deg)
      0  Precone        - Blade precone (deg)
----- I/O Settings -----
"Test01"  OutFileRoot   - Root name for any output files (use "" for .dvr rootname) (-)
True      TabDel        - When generating formatted output (OutForm=True), make output tab-delimited (fixed-width otherwise) (flag)
"ES10.3E2" OutFmt       - Format used for text tabular output, excluding the time channel. Resulting field should be 10 characters. (quoted string)
True      Beep          - Beep on exit (flag)
----- Combined-Case Analysis -----
      1  NumCases      - Number of cases to run
WndSpeed  ShearExp      RotSpd      Pitch      Yaw      dT      Tmax
(m/s)     (-)           (rpm)       (deg)       (deg)    (s)     (s)
5.000000E+00 0.000000E+00 7.190000E+01 3.000000E+00 0.000000E+00 3.970000E-02 8.345000E-01
```

Appendix B. Example AeroDyn v15.04.* Primary Input File

```
----- AERODYN v15.04.* INPUT FILE -----
Description line that will be printed in the output file and written to the screen.
===== General Options =====
True      Echo          - Echo the input to "<rootname>.AD.ech"? (flag)
"default" DTAero        - Time interval for aerodynamic calculations {or "default"} (s)
          1 WakeMod     - Type of wake/induction model (switch) {0=none, 1=BEMT}
          1 AFAeroMod   - Type of blade airfoil aerodynamics model (switch) {1=steady model, 2=Beddoes-Leishman unsteady model} [must be 1 when linearizing]
          0 TwrPotent    - Type tower influence on wind based on potential flow around the tower (switch) {0=none, 1=baseline potential flow, 2=potential flow...}
False     TwrShadow    - Calculate tower influence on wind based on downstream tower shadow? (flag)
False     TwrAero      - Calculate tower aerodynamic loads? (flag)
False     FrozenWake   - Assume frozen wake during linearization? (flag) [used only when WakeMod=1 and when linearizing]
False     CavitCheck   - Perform cavitation check? (flag)
===== Environmental Conditions =====
          1.246 AirDens  - Air density (kg/m^3)
          1.4639E-05 KinVisc - Kinematic air viscosity (m^2/s)
          333.3 SpdSound - Speed of sound (m/s)
          101325 Patm    - Atmospheric pressure (Pa) [used only when CavitCheck=True]
          2000 Pvp      - Vapour pressure of fluid (Pa) [used only when CavitCheck=True]
          0.6 FluidDepth - Water depth above mid-hub height (m) [used only when CavitCheck=True]
===== Blade-Element/Momentum Theory Options ===== [used only when WakeMod=1]
          1 SkewMod     - Type of skewed-wake correction model (switch) {1=uncoupled, 2=Pitt/Peters, 3=coupled} [used only when WakeMod=1]
f         TipLoss     - Use the Prandtl tip-loss model? (flag) [used only when WakeMod=1]
f         HubLoss     - Use the Prandtl hub-loss model? (flag) [used only when WakeMod=1]
True     TanInd       - Include tangential induction in BEMT calculations? (flag) [used only when WakeMod=1]
True     AIDrag       - Include the drag term in the axial-induction calculation? (flag) [used only when WakeMod=1]
True     TIDrag       - Include the drag term in the tangential-induction calculation? (flag) [used only when WakeMod=1 and TanInd=TRUE]
          1E-05 IndToler - Convergence tolerance for BEMT nonlinear solve residual equation {or "default"} (-) [used only when WakeMod=1]
          100 MaxIter  - Maximum number of iteration steps (-) [used only when WakeMod=1]
===== Beddoes-Leishman Unsteady Airfoil Aerodynamics Options ===== [used only when AFAeroMod=2]
          1 UAMod      - Unsteady Aero Model Switch (switch) {1=Baseline model (Original), 2=Gonzalez's variant (changes in Cn,Cc,Cm), 3=Minemna/Pierce...}
FALSE    FLookup     - Flag to indicate whether a lookup for 'f' will be calculated (TRUE) or whether best-fit exponential equations will be used (FALSE);...
===== Airfoil Information =====
          1 InCol_Alfa  - The column in the airfoil tables that contains the angle of attack (-)
          2 InCol_Cl    - The column in the airfoil tables that contains the lift coefficient (-)
          3 InCol_Cd    - The column in the airfoil tables that contains the drag coefficient (-)
          4 InCol_Cm    - The column in the airfoil tables that contains the pitching-moment coefficient; use zero if there is no Cm column (-)
          0 InCol_Cpmin - The column in the airfoil tables that contains the Cpmin coefficient; use zero if there is no Cpmin column (-)
          10 NumAFiles  - Number of airfoil files used (-)
"Airfoils/UAE_VI/cylinder.dat" AFNames - Airfoil file names (NumAFiles lines) (quoted strings)
"Airfoils/UAE_VI/Mod_S809_129.dat"
"Airfoils/UAE_VI/Mod_S809_185.dat"
"Airfoils/UAE_VI/Mod_S809_242.dat"
"Airfoils/UAE_VI/Mod_S809_298.dat"
"Airfoils/UAE_VI/Mod_S809_354.dat"
"Airfoils/UAE_VI/Mod_S809_410.dat"
"Airfoils/UAE_VI/Mod_S809_600.dat"
"Airfoils/UAE_VI/Mod_S809_800.dat"
"Airfoils/UAE_VI/Mod_S809_Outboard.dat"
===== Rotor/Blade Properties =====
True     UseBlCm     - Include aerodynamic pitching moment in calculations? (flag)
"Test01_UAE_AeroDyn_blade.dat" ADB1File(1) - Name of file containing distributed aerodynamic properties for Blade #1 (-)
"Test01_UAE_AeroDyn_blade.dat" ADB1File(2) - Name of file containing distributed aerodynamic properties for Blade #2 (-) [unused if NumBl < 2]
"Test01_UAE_AeroDyn_blade.dat" ADB1File(3) - Name of file containing distributed aerodynamic properties for Blade #3 (-) [unused if NumBl < 3]
```

```

===== Tower Influence and Aerodynamics ===== [used only when TwrInflnc/=0, or TwrAero=True]
                    5 NumTwrNds - Number of tower nodes used in the analysis (-) [used only when TwrInflnc/=0, or TwrAero=True]
TwrElev            TwrDiam            TwrCd
(m)                (m)                (-)
0.000000E+00      6.000000E+00      0.000000E+00
2.000000E+01      5.500000E+00      0.000000E+00
4.000000E+01      5.000000E+00      0.000000E+00
6.000000E+01      4.500000E+00      0.000000E+00
8.000000E+01      4.000000E+00      0.000000E+00
===== Outputs =====
True              SumPrint          - Generate a summary file listing input options and interpolated properties to "<rootname>.AD.sum"? (flag)
                  4 NB1Outs          - Number of blade node outputs [0 - 9] (-)
                  1,              3,              4,              6      B1OutNd          - Blade nodes whose values will be output (-)
                  0 NTwOuts          - Number of tower node outputs [0 - 9] (-)
                  1 TwOutNd          - Tower nodes whose values will be output (-)
                  OutList          - The next line(s) contains a list of output parameters. See OutListParameters.xlsx for a listing of available output channels, (-)
"B1N1VDisx, B1N1VDisy, B1N1VDisz" ! disturbed wind velocity at Blade 1, Node 1
"B1N2VDisx, B1N2VDisy, B1N2VDisz" ! disturbed wind velocity at Blade 1, Node 2
"B1N3VDisx, B1N3VDisy, B1N3VDisz" ! disturbed wind velocity at Blade 1, Node 3
"B1N1STVx, B1N1STVy, B1N1STVz" ! structural translational velocity at Blade 1, Node 1
"B1N2STVx, B1N2STVy, B1N2STVz" ! structural translational velocity at Blade 1, Node 2
"B1N3STVx, B1N3STVy, B1N3STVz" ! structural translational velocity at Blade 1, Node 2
"RtSpeed, RtSkew, B1Azimuth"
"B1N1AxInd, B1N2AxInd, B1N3AxInd"
"B1N1Alpha, B1N2Alpha, B1N3Alpha"
"B1N1Theta, B1N2Theta, B1N3Theta"
END of input file (the word "END" must appear in the first 3 columns of this last OutList line)
-----

```

Appendix C. Example AeroDyn v15.04.* Airfoil Data Input File

```
! "S809 Airfoil, OSU data at Re=.75 Million, Clean roughness"
! "NREL/TP-442-7817 Appendix B, Viterna used aspect ratio=11"
! note that this file uses Marshall Buhl's new input file processing; start all comment lines with !
!-----
"DEFAULT"      InterpOrd      ! Interpolation order to use for quasi-steady table lookup {1=linear; 3=cubic spline; "default"} [default=3]
!-----
      1  NonDimArea      ! The non-dimensional area of the airfoil (area/chord^2) (set to 1.0 if unsure or unneeded)
      67  NumCoords      ! The number of coordinates in the airfoil shape file (including an extra coordinate for airfoil reference). Set to zero if coordinates...
! ..... x-y coordinates are next if NumCoords > 0 .....
! x-y coordinate of airfoil reference
! x/c          y/c
0.25          0
! NREL's S809 Airfoil
! x/c          y/c
1.000000     0.000000
0.996203     0.000487
0.985190     0.002373
0.967844     0.005960
0.945073     0.011024
0.917488     0.017033
0.885293     0.023458
0.848455     0.030280
0.807470     0.037766
0.763042     0.045974
0.715952     0.054872
0.667064     0.064353
0.617331     0.074214
0.567830     0.084095
0.519832     0.093268
0.474243     0.099392
0.428461     0.101760
0.382612     0.101840
0.337260     0.100070
0.292970     0.096703
0.250247     0.091908
0.209576     0.085851
0.171409     0.078687
0.136174     0.070580
0.104263     0.061697
0.076035     0.052224
0.051823     0.042352
0.031910     0.032299
0.016590     0.022290
0.006026     0.012615
0.000658     0.003723
0.000204     0.001942
0.000000     -0.000020
0.000213     -0.001794
0.001045     -0.003477
0.001208     -0.003724
0.002398     -0.005266
0.009313     -0.011499
0.023230     -0.020399
```

```

0.042320 -0.030269
0.065877 -0.040821
0.093426 -0.051923
0.124111 -0.063082
0.157653 -0.073730
0.193738 -0.083567
0.231914 -0.092442
0.271438 -0.099905
0.311968 -0.105281
0.353370 -0.108181
0.395329 -0.108011
0.438273 -0.104552
0.481920 -0.097347
0.527928 -0.086571
0.576211 -0.073979
0.626092 -0.060644
0.676744 -0.047441
0.727211 -0.035100
0.776432 -0.024204
0.823285 -0.015163
0.866630 -0.008204
0.905365 -0.003363
0.938474 -0.000487
0.965086 0.000743
0.984478 0.000775
0.996141 0.000290
1.000000 0.000000

```

```

! -----
!           1  NumTabs           ! Number of airfoil tables in this file.  Each table must have lines for Re and Ctrl.
! -----
! data for table 1
! -----
0.75  Re           ! Reynolds number in millions
0     Ctrl        ! Control setting (must be 0 for current AirfoilInfo)
true  InclUAdata  ! Is unsteady aerodynamics data included in this table? If TRUE, then include 30 UA coefficients below this line
! -----
-0.38 alpha0      ! 0-lift angle of attack, depends on airfoil.
15.3  alpha1      ! Angle of attack at f=0.7, (approximately the stall angle) for AOA>alpha0. (deg)
-15.3 alpha2      ! Angle of attack at f=0.7, (approximately the stall angle) for AOA<alpha0. (deg)
1     eta_e       ! Recovery factor in the range [0.85 - 0.95] used only for UAMOD=1, it is set to 1 in the code when flookup=True. (-)
7.12499 C_nalpha  ! Slope of the 2D normal force coefficient curve. (1/rad)
2     T_f0       ! Initial value of the time constant associated with Df in the expression of Df and f''. [default = 3]
7     T_V0       ! Initial value of the time constant associated with the vortex lift decay process; it is used in the expression of Cvn. It depends on...
1.6   T_p        ! Boundary-layer,leading edge pressure gradient time constant in the expression of Dp. It should be tuned based on airfoil experimental...
9     T_VL       ! Initial value of the time constant associated with the vortex advection process; it represents the non-dimensional time in semi-...
"Default" b1      ! Constant in the expression of phi_alpha^c and phi_q^c. This value is relatively insensitive for thin airfoils, but may be different...
"Default" b2      ! Constant in the expression of phi_alpha^c and phi_q^c. This value is relatively insensitive for thin airfoils, but may be different...
0.5   b5         ! Constant in the expression of K''_q,Cm_q^nc, and k_m,q. [from experimental results, defaults to 5]
"Default" A1      ! Constant in the expression of phi_alpha^c and phi_q^c. This value is relatively insensitive for thin airfoils, but may be different...
"Default" A2      ! Constant in the expression of phi_alpha^c and phi_q^c. This value is relatively insensitive for thin airfoils, but may be different...
"Default" A5      ! Constant in the expression of K''_q,Cm_q^nc, and k_m,q. [from experimental results, defaults to 1]
18.269 S1        ! Constant in the f curve best-fit for alpha0<=AOA<=alpha1; by definition it depends on the airfoil. [ignored if UAMod<>1]
-11.324 S2        ! Constant in the f curve best-fit for AOA> alpha1; by definition it depends on the airfoil. [ignored if UAMod<>1]
18.269 S3        ! Constant in the f curve best-fit for alpha2<=AOA< alpha0; by definition it depends on the airfoil. [ignored if UAMod<>1]
-11.324 S4        ! Constant in the f curve best-fit for AOA< alpha2; by definition it depends on the airfoil. [ignored if UAMod<>1]
1.9408 Cn1       ! Critical value of C0n at leading edge separation. It should be extracted from airfoil data at a given Mach and Reynolds number. It...
-0.8  Cn2        ! As Cn1 for negative AOAs.

```

```

"Default" St_sh      ! Strouhal's shedding frequency constant. [default = 0.19]
0.0016 Cd0        ! 2D drag coefficient value at 0-lift.
-0.0328 Cm0       ! 2D pitching moment coefficient about 1/4-chord location, at 0-lift, positive if nose up. [If the aerodynamics coefficients table does...
0 k0             ! Constant in the \hat(x)_cp curve best-fit; = (\hat(x)_AC-0.25). [ignored if UAMod<>1]
0 k1             ! Constant in the \hat(x)_cp curve best-fit. [ignored if UAMod<>1]
0 k2             ! Constant in the \hat(x)_cp curve best-fit. [ignored if UAMod<>1]
0 k3             ! Constant in the \hat(x)_cp curve best-fit. [ignored if UAMod<>1]
0 k1_hat        ! Constant in the expression of Cc due to leading edge vortex effects. [ignored if UAMod<>1]
"Default" x_cp_bar ! Constant in the expression of \hat(x)_cp^v. [ignored if UAMod<>1, default = 0.2]
"DEFAULT" UACutout ! Angle of attack above which unsteady aerodynamics are disabled (deg). [Specifying the string "Default" sets UACutout to 45 degrees]
"DEFAULT" filtCutOff ! Cut-off frequency (-3 dB corner frequency) for low-pass filtering the AoA input to UA, as well as the 1st and 2nd derivatives (Hz)...

```

```

!.....
! Table of aerodynamics coefficients
! Number of data lines in the following table
63 NumAlf

```

!	Alpha (deg)	C1 (-)	Cd (-)	Cm (-)
-180	0	0.1748	0	
-170	0.23	0.2116	0.4	
-160	0.46	0.3172	0.1018	
-150	0.494	0.4784	0.1333	
-140	0.51	0.6743	0.1727	
-130	0.486	0.8799	0.2132	
-120	0.415	1.0684	0.2498	
-110	0.302	1.2148	0.2779	
-100	0.159	1.2989	0.2933	
-90	0	1.308	0.2936	
-80	-0.159	1.2989	0.2933	
-70	-0.302	1.2148	0.2779	
-60	-0.415	1.0684	0.2498	
-50	-0.486	0.8799	0.2132	
-40	-0.51	0.6743	0.1727	
-30	-0.494	0.4784	0.1333	
-21.1	-0.56	0.3027	0.0612	
-19.1	-0.67	0.3069	0.0904	
-17.1	-0.79	0.1928	0.0293	
-15.2	-0.84	0.0898	-0.009	
-13.2	-0.7	0.0553	-0.0045	
-11.1	-0.63	0.039	-0.0044	
-9.2	-0.56	0.0233	-0.0051	
-7.1	-0.64	0.0131	0.0018	
-5.1	-0.42	0.0134	-0.0216	
-3.1	-0.21	0.0119	-0.0282	
-0.9	0.05	0.0122	-0.0346	
1	0.3	0.0116	-0.0405	
3.1	0.54	0.0144	-0.0455	
5.2	0.777	0.0146	-0.0507	
6.15	0.854	0.0154	-0.04555	
7.1	0.906	0.0162	-0.0404	
8.15	0.888	0.0266	-0.03625	
9.2	0.91	0.037	-0.0321	
10.3	0.927	0.045	-0.0281	
11.18	0.948	0.052	-0.0284	
12.2	0.957	0.067	-0.0322	
13.2	0.987	0.074	-0.0361	
14.3	1.009	0.089	-0.0363	
15.3	0.948	0.112	-0.0393	
16.1	0.918	0.123	-0.0398	

17.1	0.815	0.175	-0.0983
18.1	0.7	0.257	-0.1242
19.1	0.627	0.305	-0.1155
25	0.528	0.454	-0.186083486
30	0.631	0.4784	-0.2459
35	0.592	0.524	-0.2636
40	0.554	0.554	-0.2813
45	0.506	0.61	-0.29735
50	0.442	0.807	-0.3134
60	0.296	0.987	-0.3388
70	0.193	1.172	-0.3557
80	0.082	1.236	-0.363
90	0	1.249	-0.3604
100	-0.159	1.2989	-0.36
110	-0.302	1.2148	-0.3446
120	-0.415	1.0684	-0.3166
130	-0.486	0.8799	-0.28
140	-0.51	0.6743	-0.2394
150	-0.494	0.4784	-0.2001
160	-0.46	0.3172	-0.1685
170	-0.23	0.2116	-0.5
180	0	0.1748	0

Appendix D. Example AeroDyn v15.04.* Blade Data Input File

```

----- AERODYN v15.04.* BLADE DEFINITION INPUT FILE -----
Description line for this file -- file corresponds to inputs in Test01_UAE_AeroDyn.dat
===== Blade Properties =====
 23      NumBlNds      - Number of blade nodes used in the analysis (-)
  BlSpn    BlCrvAC    BlSwpAC    BlCrvAng    BlTwist    BlChord    BlAFID
 (m)      (m)      (m)      (deg)      (deg)      (m)      (-)
0.0       0.0       0.0       0.0       0.000     0.219     1
0.1360    0.0       0.0       0.0       0.000     0.219     1
0.4481    0.0       0.0       0.0       -0.098    0.181     1
0.8001    0.0       0.0       0.0       19.423    0.714     3
1.0767    0.0       0.0       0.0       14.318    0.711     4
1.2779    0.0       0.0       0.0       10.971    0.691     5
1.4958    0.0       0.0       0.0       8.244     0.668     6
1.7137    0.0       0.0       0.0       6.164     0.647     7
1.9149    0.0       0.0       0.0       4.689     0.627     7
2.1160    0.0       0.0       0.0       3.499     0.606     8
2.3340    0.0       0.0       0.0       2.478     0.584     8
2.5520    0.0       0.0       0.0       1.686     0.561     8
2.7530    0.0       0.0       0.0       1.115     0.542     8
2.9542    0.0       0.0       0.0       0.666     0.522     8
3.1721    0.0       0.0       0.0       0.267     0.499     8
3.3900    0.0       0.0       0.0       -0.079    0.478     8
3.5912    0.0       0.0       0.0       -0.381    0.457     9
3.7924    0.0       0.0       0.0       -0.679    0.437     9
3.9684    0.0       0.0       0.0       -0.933    0.419     9
4.1444    0.0       0.0       0.0       -1.184    0.401    10
4.3456    0.0       0.0       0.0       -1.466    0.381    10
4.5216    0.0       0.0       0.0       -1.711    0.363    10
4.5970    0.0       0.0       0.0       -1.711    0.363    10

```

Appendix E. List of Output Channels

This is a list of all possible output parameters for the AeroDyn module. The names are grouped by meaning, but can be ordered in the OUTPUTS section of the AeroDyn input file as you see fit. $B\alpha N\beta$, refers to output node β of blade α , where α is a number in the range [1,3] and β is a number in the range [1,9], corresponding to entry β in the *BlOutNd* list. $TwN\beta$ refers to output node β of the tower and is in the range [1,9], corresponding to entry β in the *TwOutNd* list.

The local tower coordinate system is shown in Figure 2 of section 4.3.7 and the local blade coordinate system is shown in Figure 3 and Figure 4 below. Figure 4 also shows the direction of the local angles and force components.

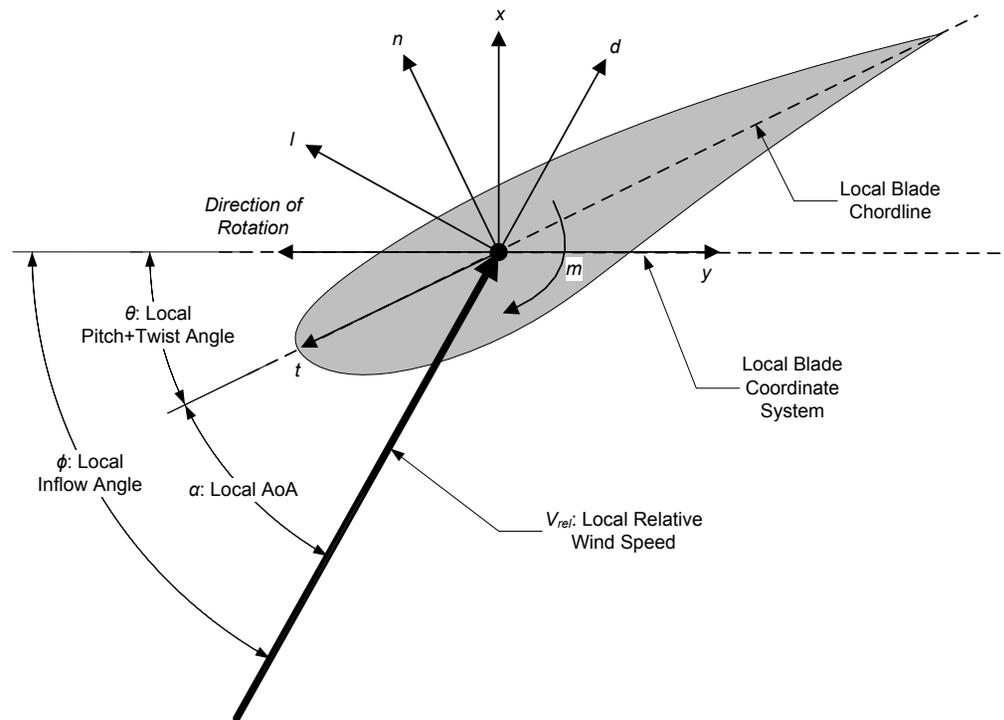


Figure 4. AeroDyn Local Blade Coordinate System (Looking Toward the Tip, from the Root) – l : Lift, d : Drag, m : Pitching, x : Normal (to Plane), y : Tangential (to Plane), n : Normal (to Chord), and t : Tangential (to Chord)

Channel Name(s)	Units	Description
<i>Tower</i>		
$T_{wN\beta}V_{Undx}$, $T_{wN\beta}V_{Undy}$, $T_{wN\beta}V_{Undz}$	(m/s), (m/s), (m/s)	Undisturbed wind velocity at $T_{wN\beta}$ in the local tower coordinate system
$T_{wN\beta}STV_x$, $T_{wN\beta}STV_y$, $T_{wN\beta}STV_z$	(m/s), (m/s), (m/s)	Structural translational velocity at $T_{wN\beta}$ in the local tower coordinate system
$T_{wN\beta}V_{rel}$	(m/s)	Relative wind speed at $T_{wN\beta}$
$T_{wN\beta}DynP$	(Pa)	Dynamic pressure at $T_{wN\beta}$
$T_{wN\beta}Re$	(-)	Reynolds number (in millions) at $T_{wN\beta}$
$T_{wN\beta}M$	(-)	Mach number at $T_{wN\beta}$
$T_{wN\beta}F_{dx}$, $T_{wN\beta}F_{dy}$	(N/m), (N/m)	Drag force per unit length at $T_{wN\beta}$ in the local tower coordinate system
<i>Blade</i>		
$B_{\alpha}Azimuth$	(deg)	Azimuth angle of B_{α}
$B_{\alpha}Pitch$	(deg)	Pitch angle of B_{α}
$B_{\alpha N\beta}Cl_{rnc}^*$	(m)	Tower clearance at $B_{\alpha N\beta}^*$
$B_{\alpha N\beta}V_{Undx}$, $B_{\alpha N\beta}V_{Undy}$, $B_{\alpha N\beta}V_{Undz}$	(m/s), (m/s), (m/s)	Undisturbed wind velocity at $B_{\alpha N\beta}$ in the local blade coordinate system
$B_{\alpha N\beta}V_{Disx}$, $B_{\alpha N\beta}V_{Disy}$, $B_{\alpha N\beta}V_{Disz}$	(m/s), (m/s), (m/s)	Disturbed wind velocity at $B_{\alpha N\beta}$ in the local blade coordinate system
$B_{\alpha N\beta}STV_x$, $B_{\alpha N\beta}STV_y$, $B_{\alpha N\beta}STV_z$	(m/s), (m/s), (m/s)	Structural translational velocity at $B_{\alpha N\beta}$ in the local blade coordinate system
$B_{\alpha N\beta}V_{rel}$	(m/s)	Relative wind speed at $B_{\alpha N\beta}$
$B_{\alpha N\beta}DynP$	(Pa)	Dynamic pressure at $B_{\alpha N\beta}$
$B_{\alpha N\beta}Re$	(-)	Reynolds number (in millions) at $B_{\alpha N\beta}$
$B_{\alpha N\beta}M$	(-)	Mach number at $B_{\alpha N\beta}$
$B_{\alpha N\beta}V_{Indx}$, $B_{\alpha N\beta}V_{Indy}$	(m/s), (m/s)	Axial and tangential induced wind velocity at

* $B_{\alpha N\beta}Cl_{rnc}$ is based on the absolute distance to the nearest point in the tower from $B_{\alpha N\beta}$ minus the local tower radius, in the deflected configuration. Please note that this clearance is only approximate because the calculation assumes that the blade is a line with no volume (however, the calculation does use the local tower radius). When $B_{\alpha N\beta}$ is above the tower top (or below the tower base), the absolute distance to the tower top (or base) minus the local tower radius, in the deflected configuration, is output.

		$B\alpha N\beta$
$B\alpha N\beta A_{xInd}$, $B\alpha N\beta T_{nInd}$	(-), (-)	Axial and tangential induction factors at $B\alpha N\beta$
$B\alpha N\beta \alpha$, $B\alpha N\beta \theta$, $B\alpha N\beta \phi$, $B\alpha N\beta \text{Curve}$	(deg), (deg), (deg), (deg)	AoA, pitch+twist angle, inflow angle, and curvature angle at $B\alpha N\beta$
$B\alpha N\beta C_l$, $B\alpha N\beta C_d$, $B\alpha N\beta C_m$, $B\alpha N\beta C_{pmin}$ $B\alpha N\beta C_x$, $B\alpha N\beta C_y^\dagger$, $B\alpha N\beta C_n$, $B\alpha N\beta C_t$	(-), (-), (-), (-) (-), (-), (-), (-)	Lift force, drag force, pitching moment, minimum pressure, normal force (to plane), tangential force (to plane) [†] , normal force (to chord), and tangential force (to chord) coefficients at $B\alpha N\beta$
$B\alpha N\beta \text{SigCr}$, $B\alpha N\beta \text{SgCav}$	(-), (-)	Critical cavitation number—based on undisturbed freestream pressure at the node, the vapor pressure of the fluid, and the relative velocity—and the local cavitation number—given by the minimum pressure coefficient—at $B\alpha N\beta$
$B\alpha N\beta F_l$, $B\alpha N\beta F_d$, $B\alpha N\beta M_m$, $B\alpha N\beta F_x$, $B\alpha N\beta F_y^\dagger$, $B\alpha N\beta F_n$, $B\alpha N\beta F_t$	(N/m), (N/m), (N·m/m), (N/m), (N/m), (N/m), (N/m)	Lift force, drag force, pitching moment, normal force (to plane), tangential force (to plane) [†] , normal force (to chord), and tangential force (to chord) per unit length at $B\alpha N\beta$
<i>Rotor</i>		
RtSpeed	(rpm)	Rotor speed
RtTSR	(-)	Rotor tip-speed ratio
RtV_{Avgxh} , RtV_{Avgyh} , RtV_{Avgzh}	(m/s), (m/s), (m/s)	Rotor-disk-averaged relative wind velocity in the hub coordinate system (not including induction)
RtSkew	(deg)	Rotor inflow-skew angle
$RtAeroF_{xh}$, $RtAeroF_{yh}$, $RtAeroF_{zh}$, $RtAeroM_{xh}$, $RtAeroM_{yh}$, $RtAeroM_{zh}$	(N), (N), (N) (N·m), (N·m), (N·m)	Total rotor aerodynamic load in the hub coordinate system
RtAeroPwr	(W)	Rotor aerodynamic power
RtArea	(m ²)	Rotor swept area
$RtAeroC_p$, $RtAeroC_q$, $RtAeroC_t$	(-), (-), (-)	Rotor aerodynamic power, torque, and thrust coefficients

[†] Positive c_y and F_y are in the direction of rotation, opposite local y , by convention.

Appendix F. Major Changes in AeroDyn

AeroDyn v15 and newer represent a complete overhaul from earlier version of AeroDyn to (1) fix underlying problems with the original theoretical treatments, (2) introduce improved aerodynamic physics, (3) enable modeling of highly flexible and non-straight blades, and (4) support the unique features of the FAST modularization framework. This appendix outlines significant modifications to AeroDyn made with each public release, starting with v15.00.

v15.04 (April 2017)

Version 15.04 integrates with the FAST v8 software v8.17.

- **Primary input file changes**
 - *CavitCheck* was added. This variable gives the user the option to perform a cavitation inception check.
 - *Patm*, *Pvap* and *FluidDepth* were added. These variables are used in the cavitation check.
- **Output file changes**
 - Added output channels for the minimum pressure coefficient, critical cavitation, and local cavitation numbers at blade nodes.
- **Airfoil data input file changes**
 - Added an optional *Cpmin* to the airfoil data files, which is required when *CavitCheck* = TRUE.
- **New or modified aerodynamics**
 - Added a feature that turns off the cavitation check if there is no data. If the user flags a cavitation check but does not input *Cpmin* data, a warning is given and the cavitation flag is set to *false*.
 - Improved the BEMT solution algorithm as follows
 - BEMT now functions for the case where the undisturbed velocity along the x-direction of the local blade coordinate system (V_x) is less than zero.
 - BEMT no longer aborts when a valid value of the inflow angle (ϕ) cannot be found; in this case, the inflow angle is computed geometrically (without induction).
 - The inflow angle (ϕ) is now initialized on the first call instead of using $\phi=0$, giving better results during simulation start up.
 - When hub- and/or tip-loss are enabled (*HubLoss* = True and/or *TipLoss* = True), tangential induction (a') is set to 0 instead of -1 at the root and/or tip, respectively (axial induction (a) is still set to 1 at the root and/or tip).
 - Fixed a bug whereby when hub- and/or tip-loss are enabled (*HubLoss* = True and/or *TipLoss* = True) along with the Pitt/Peters skewed-wake correction

(*SkewMod* = 2), BEMT no longer modifies the induction factors at the hub and/or tip, respectively.

- Made the BEMT solution more efficient.
- Fixed a bug whereby the time series was effected after the linearization analysis with AeroDyn coupled to FAST when frozen wake is enabled (*FrozenWake* = True).
- Fixed a bug in the calculation of wind loads on the tower whereby the tower displacement was used in place of the tower velocity.
- Fixed minor bugs in the unsteady airfoil aerodynamics model.
- Tower strikes detected by the models to calculate the influence of the tower on the wind local to the blade are now treated as fatal errors instead of severe errors.

v15.03 (July 2016)

Version 15.03 integrates with the FAST v8 software v8.16.00a-bjj.

- **Primary input file changes**
 - *FrozenWake* was added. This variable gives the user the option to recalculate the induction or use frozen wake during linearization analyses with AeroDyn coupled to FAST.
- **New or modified aerodynamics**
 - Added the ability to linearize AeroDyn when coupled to FAST, as part of the linearization of the full coupled solution.

v15.02 (April 2016)

Version 15.02 integrates with the FAST v8 software v8.15.00a-bjj.

- **Primary input file changes**
 - *IndToler* can now be specified as "default". The default in single precision is 5E-5; the default in double precision is 5E-10.
- **Airfoil data input file changes**
 - *InterpOrd* was added. This variable gives the user an option to use either linear (*InterpOrd* = 1) or cubic-spline (*InterpOrd* = 3) methods to interpolate the quasi-steady table lookup. The "default" option will use cubic splines.
 - *filtCutOff* was added to the parameters specified for UA. This is the cut-off frequency (-3 dB corner frequency) in Hz for low-pass filtering the AoA input to UA, as well as the 1st and 2nd derivatives. *filtCutOff* can be specified as "default", which will set it to be 20 Hz.
 - When specifying coordinates for the airfoil shape, we added the aerodynamic center (reference point for the airfoil lift and drag forces, likely not on the surface

of the airfoil) as the first point to be specified. The airfoil shape is currently unused by AeroDyn, but when AeroDyn is coupled to FAST, the airfoil shape will be used by FAST for blade surface visualization when enabled.

- **New or modified aerodynamics**
 - Improved the BEMT solution algorithm, addressed numerical issues, and cleaned up the code.
 - Corrected the González and Minnema/Pierce UA models to match documented theory, addressed numerical issues, and enabled UA for the first time. **While all of the UA models are documented in this manual, the original B-L model is not yet functional. Testing has shown that the González and Minnema/Pierce models produce reasonable hysteresis of the normal force, tangential force, and pitching-moment coefficients if the UA model parameters are set appropriately for a given airfoil, Reynold's number, and/or Mach number. However, the results will differ a bit from earlier versions of AeroDyn, (which was based on the Minnema/Pierce extensions to B-L) even if the default UA model parameters are used, due to differences in the UA model logic between the versions. We recommend that users run test cases with uniform wind inflow and fixed yaw error (e.g., through the standalone AeroDyn driver) to examine the accuracy of the normal force, tangential force, and pitching-moment coefficient hysteresis and to adjust the UA model parameters appropriately.**
- **Output file changes**
 - Added output channels for blade-to-tower clearance.

v15.00 (September 2015)

- The AeroDyn v15 module interfaces with FAST v8.12.
- The AeroDyn v15 source code has been entirely rewritten and is now fully compatible with the requirements of the FAST modularization framework.
- The AeroDyn v15 module can be run uncoupled from FAST by a standalone driver code (in addition to the FAST v8 interface).
- The InflowWind v3 routines have been converted from a submodule of AeroDyn to a core module of FAST v8. So, undisturbed wind inflow is no longer calculated within AeroDyn, but is passed into AeroDyn from the driver (either FAST or the standalone driver). Unlike previous versions, InflowWind v3 supports HAWC wind file formats and arbitrary wind directions for all wind file types.
- The format of the AeroDyn v15 input files (including the airfoil data) is entirely different.
- The BEM solution method in AeroDyn v15 is improved and more robust and now treats structural velocities identically to wind velocities (the induction calculation is based on the relative velocity between the wind and structure, whereas previously, structural velocities were only included in a few terms). As a result, small differences in

tangential induction are expected under most conditions and overall differences are expected for large structural motions.

- The Generalized Dynamic Wake (GDW) model is not yet available in AeroDyn v15.
- The [DWM interface](#) is not yet available in AeroDyn v15.
- Airfoil data is now interpolated via cubic splines (previously, linear interpolation was used). As a result, small differences in the aerodynamic loads are expected when the airfoil data used is coarse. Moreover, the interpolation of airfoil data based on Reynolds number or aerodynamic-control setting (e.g., flaps) is not yet available in AeroDyn v15.
- The AeroDyn v15 module supports three UA modeling options: the original theoretical developments of B-L, extensions to the B-L developed by González, and extensions to the B-L model developed by Minnema/Pierce (previously, only the Minnema/Pierce extension was available).
- The AeroDyn v15 module supports nonstraight blades, highly flexible blades, and geometrical differences between blades (previously, only identical straight blades were considered and structural motions were not handled consistently in all terms).
- The tower influence on wind in AeroDyn v15 accounts for deflections/displacements of the tower (previously, the tower was assumed to be fixed and rigid).
- The tower aerodynamic drag is available for floating offshore wind turbines (previously, tower drag was only available for land-based and fixed offshore wind turbines).
- Blade and tower analysis nodes in AeroDyn v15 no longer need to be placed at element centers; however, nodes must be placed at the blade root and tip and tower base and top. When AeroDyn v15 is coupled to FAST, blade and tower discretizations are independent of discretizations in the structural code.
- The AeroDyn v15 module supports many new output channels.