Deep**Lines** Wind turbine Example



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### TABLE OF CONTENTS

1		5
2	REFERENCES	7
3	BUILDING THE MODEL	8
3.1	Model component: HAWT	8
3.2	Model component: Freing the hub	18
3.3	Model component: Wind	19
3.4	Wind turbine properties	20
3.5	Drag/lift database: foil profiles	23
3.6	Environment set	24
4	STARTUP	26
4.1	Single analysis	26
4.2	Analysis set	29
5	RESULTS	31
5.1	Wind, Rotor and generator	31
-		
6	ANALYSES AND ANALYSIS SETS	33
<b>6</b> 6.1	Running an analysis	<b>33</b> 33
<b>6</b> 6.1 6.2	ANALYSES AND ANALYSIS SETS Running an analysis Prod_vr	<b>33</b> 33 33
6 6.1 6.2 6.3	ANALYSES AND ANALYSIS SETS         Running an analysis         Prod_vr         Prod_vr_90	
6 6.1 6.2 6.3 6.4	ANALYSES AND ANALYSIS SETS         Running an analysis         Prod_vr         Prod_vr_90         Prod_vr_HH	33 33 34 35
6 6.1 6.2 6.3 6.4 6.5	ANALYSES AND ANALYSIS SETS         Running an analysis         Prod_vr.         Prod_vr_90         Prod_vr_HH.         Prod_vr_turb	<b>33</b> 33 34 35 36
6 6.1 6.2 6.3 6.4 6.5 6.6	ANALYSES AND ANALYSIS SETS         Running an analysis         Prod_vr.         Prod_vr_90         Prod_vr_90         Prod_vr_HH         Prod_vr_turb         Prod_vr_startup_80s, 100s and 120s	<b>33</b> 33 34 35 36 37
6 6.1 6.2 6.3 6.4 6.5 6.6 6.7	ANALYSES AND ANALYSIS SETS         Running an analysis         Prod_vr.         Prod_vr_90         Prod_vr_90         Prod_vr_HH         Prod_vr_turb         Prod_vr_startup_80s, 100s and 120s         Prod_vr_startup_x	<b>33</b> 33 34 35 36 37 38
6 6.1 6.2 6.3 6.4 6.5 6.6 6.7 6.8	ANALYSES AND ANALYSIS SETS         Running an analysis         Prod_vr_90         Prod_vr_90         Prod_vr_HH         Prod_vr_turb         Prod_vr_startup_80s, 100s and 120s         Prod_vr_90_x	<b>33</b> 33 34 35 36 37 38 38
6 6.1 6.2 6.3 6.4 6.5 6.6 6.7 6.8 6.9	ANALYSES AND ANALYSIS SETS         Running an analysis         Prod_vr_m         Prod_vr_90         Prod_vr_90         Prod_vr_HH         Prod_vr_turb         Prod_vr_startup_80s, 100s and 120s         Prod_vr_90_x         Prod_vr_90_x_1	<b>33</b> 33 34 35 36 37 38 38 38 39
6 6.1 6.2 6.3 6.4 6.5 6.6 6.7 6.8 6.9 6.10	ANALYSES AND ANALYSIS SETS         Running an analysis         Prod_vr.         Prod_vr_90         Prod_vr_HH         Prod_vr_turb         Prod_vr_startup_80s, 100s and 120s         Prod_vr_startup_x         Prod_vr_90_x         Prod_vr_90_x_1         Parked_x	<b>33</b> 33 34 35 36 36 37 38 38 38 39 40
6 6.1 6.2 6.3 6.4 6.5 6.6 6.7 6.8 6.9 6.10 6.11	ANALYSES AND ANALYSIS SETS         Running an analysis         Prod_vr.         Prod_vr_90         Prod_vr_90         Prod_vr_HH         Prod_vr_turb         Prod_vr_startup_80s, 100s and 120s         Prod_vr_startup_x         Prod_vr_90_x         Prod_vr_90_x         Prod_vr_90_at_1         Parked_x         Modal_Global	<b>33</b> 33 33 34 35 36 36 37 38 38 38 39 40 41
6 6.1 6.2 6.3 6.4 6.5 6.6 6.7 6.8 6.9 6.10 6.11 6.12	ANALYSES AND ANALYSIS SETS         Running an analysis         Prod_vr.         Prod_vr90         Prod_vr90         Prod_vr_HH.         Prod_vr_turb         Prod_vr_startup_80s, 100s and 120s         Prod_vr_startup_x         Prod_vr_90_x         Prod_vr_90_x_1         Parked_x         Modal_Global         DLC_example.	<b>33</b> 33 33 34 35 36 36 37 38 38 38 39 40 41 42
6 6.1 6.2 6.3 6.4 6.5 6.6 6.7 6.8 6.9 6.10 6.11 6.12 6.13	ANALYSES AND ANALYSIS SETS         Running an analysis         Prod_vr.         Prod_vr_90         Prod_vr_90         Prod_vr_HH         Prod_vr_turb         Prod_vr_startup_80s, 100s and 120s         Prod_vr_startup_x         Prod_vr_90_x         Prod_vr_90_x_1         Parked_x         Modal_Global         DLC_example         DLC_Parked	33 33 33 34 35 35 36 37 38 38 38 39 40 40 41 42 44
6 6.1 6.2 6.3 6.4 6.5 6.6 6.7 6.8 6.9 6.10 6.11 6.12 6.13 6.14	ANALYSES AND ANALYSIS SETS         Running an analysis         Prod_vr.         Prod_vr90         Prod_vr_HH         Prod_vr_turb         Prod_vr_startup_80s, 100s and 120s         Prod_vr_startup_x         Prod_vr_90_x         Prod_vr_90_x_1         Parked_x         Modal_Global         DLC_example         DLC_example_startup	33 33 33 34 34 35 35 36 37 38 38 39 40 40 41 41 42 44 44



7.1	Coordinate systems for HAWT	.46
7.2	Profile properties	.49
7.3	Pitch angle and attack angle	.50
7.4	Coupling between the mechanical and Aerodynamic model	.51
7.5	Turbulent winds	.52



### 1 INTRODUCTION

This document presents an example of a fixed horizontal axis wind turbine (HAWT) and its setup in DeepLines WIND as well as the results which can be post-processed.

A Blade Element Momentum (BEM) model is used to model the aerodynamics. Aerodynamic coefficients are used to calculate transverse and longitudinal forces on blades. Secondary effects such as Tip loss, Hub loss, Tower Shadow, Dynamic Stall, Skewed Effect, Dynamic inflow or 3D Effect can also be modelled but are not detailed in this document. Documentation on these cases can be found in [3]. The fluid description (density and viscosity) can also be modified in the sea&ground panel.

At the beginning of each time step, a) the mechanical solver provides information on positions, velocities, and accelerations at blades nodes as well as wind velocities data and b) the controller is called. The aerodynamic solver computes the resultant forces on each beam element. Within a time step, the aerodynamic forces are considered constant and are used to load the blades until convergence

The example presented here is the NREL offshore 5MW baseline wind turbine with tower properties used for the OC4-DeepCwind semisubmersible. The model is shown below. This wind turbine is a conventional three-bladed upwind variable-speed variable blade-pitch-to-feather-controlled turbine.

The rotor blades are held by the hub. The hub rotates with the powertrain (shaft, gearbox and generator). The hub is initially clamped for static analysis then released for the dynamic phase. The nacelle is linked by 2 pin connections (acting as bearings) to the shaft. The nacelle is supported by the tower which is clamped at its bottom.





Figure 1-1 : Example of Wind turbine in DeepLines WIND



# 2 **REFERENCES**

Ref.	Document Number	Document Title	Rev.
[1]	NREL/TP-500-38060	Definition of a 5-MW Reference Wind Turbine for Offshore System Development	February 2009
[2]	NREL/TP-5000-60601	Definition of the Semisubmersible Floating System for Phase II of OC4	September 2014
[3]		Aerodeep 2.2 User Manual	Jan. 21



# 3 BUILDING THE MODEL

All orientations and conventions are provided in Section 7.

## 3.1 MODEL COMPONENT: HAWT

An HAWT is represented by lines and rigid bodies connected together. An HAWT is made of several subcomponents which are described in this section. HAWT subcomponents use a library named AeroDeep [3] which includes a series of routine written to perform the aerodynamic calculations for aeroelastic simulations of the blades.

An HAWT is added to the model by clicking on the HAWT toolbar button (see Figure 3-1).

This automatically created a shaft, a hub, a nacelle, a tower, and by default 3 blades (see Figure 3-2). The number of blades can be modified afterwards.





Figure 3-1 : HAWT toolbar button (in red square)

Figure 3-2 : Detail of a turbine in model browser

### 3.1.1 General data

General data are:

- The name of the turbine, if several turbines are modelled it is important to give them an appropriate name: it is called "HAWT" in this example
- The position of the origin in the global coordinate system (when the turbine is free or clamped). This is the position of the bottom of the tower. Here it is 10 m above the MSL.
- The connection of the HAWT to other objects. In this example it is anchored and clamped which means that the bottom of the turbine does not move.
- The heading (generally not used, it is better practice to rotate the nacelle at the beginning of simulation.)

Object:	HAWT	~	
Name:	HAWT		Heading / Ox: 0 deg.
Coord. of reference point	×(m) Y (m) Z (m) 0 0 10	State \ Linked to     Attach point       Anchored	Connection       Clamp     Clit connection

Figure 3-3 : Turbine general data

### 3.1.2 Turbine

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This panel allows defining that the turbine is upwind, rotating clockwise and has 3 blades.

The tower altitude is automatically updated with the tower length (see Tower sheet 3.1.4) and coordinates of reference point (see 3.1.1) and indicate that the top of the tower of 87.6 m above the MSL.

Several dimensions are defined as illustrated by the drawing provided in the sheet.

0	Downwind		Clock	wise				
					prebend	Precone (regative as shown)	144	HubCM (negative as shown
Tower alt	Z	87.600	m	-	-			HubRad
	Twr2Shft	1.960	m			i l		
Shaft	OverHa	-5.000	m					
	ShftTilt	-5.000	deg.			N f		et tot
	HubRad	1.500	m	-				17
нир	HubCM	0.000	m		TIpRa			
DL 1	Precone	-2.500	deg.		d			Hub C.M.
Blade	TipRad	63.000	m				NacCMan	-Nacelle C.M.
	NacCMxn	1.900	m	-	Y			ShftTil
Nacelle	NacCMzn	1.750	m			1 m	-	Twr2Shft
					Hub C.M.	12	N	acCMzn
						OverHa Inegative as a	Ing	
								TowerHt

### Figure 3-4 : Turbine general setup

### 3.1.3 Blades

Blades are modelled using beam finite elements. The "GENERIC" line type is used in DeepLines. Blades are clamped to the hub.



The shape and mechanical twist of the blades gives the equilibrium reference of the object ("User-defined shape"). The blade can be provided in an encrypted file or fully described. The shape of a fully described blade (which is the case here) is shown in the graphic interface and a visual check of the shape can be done (chord variations with length). The blade profiles are discussed in section 3.5.

The 3 blades are similar and modifying values in the blade editor will modify the 3 blades.

In this example, no added mass is used for the blades. It would have been defined in a variation table otherwise and selected here.

The blade is divided in 17 sections. A different line type is defined for each blade section. Sections are defined from hub to tip. Data can be modified in the blade interface or in the line type interface.

- 17 sections are defined for the aerodynamic properties in NREL specification document [1],
- the structural properties are merged to correspond to these 17 sections.

The total length of the blade (total of length of each section) must be consistent with the length defined in the turbine sheet (= TipRad – HubRad) otherwise an error message will appear.

For each section, the following data should be provided. Data for structural and aerodynamic calculations are provided and are summarised in the table below.

Number of sections	Define the blade mesh
Damping coefficients (Rayleigh coefficients)	Damping rate or coefficent expressed in $\beta K$
For every blade section	
Section Length (m)	
Chord (m)	Chord
Structural twist (deg)	Often called Elastic frame; See section 7.2
Aerodynamic pitch (deg)	Initial blade pitch
Profile name	Profile is defined in drag/lift database/aerodynamic
	In-plane and Out of plane blade prebend
IP&OP prebend (m)	Pre-bend
Dry weight (kN/m)	This is a weight, e.g. a force not a linear mass.
Flap & Edge bending stiffness (N.m <sup>2</sup> )	Stiffness' are defined wrt the elastic frame The bending stiffness is multiplied by the curvature to get the bending moment. Flapwise $(\iint Ex^2d xdy = E \iint x^2dxdy = ES_y)$ Edgewise $(\iint Ey^2dxdy = E \iint y^2dxdy = ES_x)$ (should be > Ei flap)
Torsion stiffness (N.m <sup>2</sup> )	The torsion stiffness is multiplied by the torsion strain (curvature along the blade axis) to get the torsion moment. $(\iint G(x^2 + y^2)dxdy = G\iint (x^2 + y^2)dxdy = EGI_z)$
Axial stiffness (N)	The axial stiffness is multiplied by the axial strain to get the axial force.
Inertia flap and edge (kg.m)	Inertia are expressed in the mass orientation frame at the center of gravity. They are associated with the accelerations to get the inertia forces. $(\iint \rho x^2 dx dy = \rho \iint x^2 dx dy = \int r_{ix}^2 dm = J_{yy})$
i orsional inertia (kg.m)	Applied at Center Of Gravity

Aero centre (X, Y) coordinates in the section (m)	See section 7.2; Application point of Aerodynamic efforts
Centre of gravity (X, Y) coordinates in the section (m)	See section 7.2; Application point of inertia terms
Mass axis orientation (deg)	See section 7.2, Inertia matrix orientation
Shear centre (X,Y) coordinates in the section (m)	See section 7.2
Flap & Edge Shear stiffness (N)	In the elastic frame at shear centre
Bending-Torsion stiffness (N/m <sup>2</sup> )	In the elastic frame at shear center

Table 3-1 : Blade input data (see Section 7 for orientations)

Blade orientation is shown in Figure 3-5. Z axis is positive from the hub to the blade tip.



Figure 3-5 : Blade orientation. Left 0° (production), right -90° (parked). Z is downwards here.

### 3.1.4 Tower

The tower is defined by beam elements.

The tower is clamped to the top at the Nacelle. The bottom of the tower can be anchored in space (which is the case in this example) or attached to another object (fairlead of a floater or rigid body).

A line type is automatically created with tower properties. The tower is a line divided in several segments. The number of segments is defined in "Partition".

A global drag coefficient can be defined on the tower and can depend on the Reynolds number. When defined, this drag coefficient supersedes the drag coefficients potentially defined in the segment types of the beam elements composing the tower.

This drag coefficient is used to apply wind load the tower. A specific drag coefficient is defined to compute the tower shadow which is only used by the aerodynamic solver.

In this example a global drag coefficient of 0.65 is applied and is not depending on the Reynolds number.

Tower properties are the ones for the OC4-DeepCwind semisubmersible [2]. The tower length was set to 77.6 m

The tower type is conical. Therefore, the base diameter (6.5 m) and thickness (0.027 m), top diameter (3.87 m) and thickness (0.019 m) are input. The shape of the tower can be visually checked in the GUI.

The Young modulus, and specific gravity (= steel effective density/freshwater density) are also defined. A default value of Poisson coefficient equal to 0.3 has been chosen. A default value of Rayleigh damping coefficient of 0.005 has been chosen.



No drag coefficient for tower shadow is used in this example. See Aerodeep manual for more details [3].

ower length :	77.6		m	Co	lor:	-				
Towertype										
	<ul> <li>Conic</li> </ul>	al tower				Ou	ser dei	fined		
Mechanical pro	perties					Pipe material				
						Young modu	ilus :		210	GPa
Beginn	ning of pipe					Poisson coe	fficient	2	0.3	]
Out	tside diameter:	6500		mr	n	Specific grav	vity :		8.5	
Wa	all thickness :	27		m	n					
End of	nine									
End of	pipe									
End of Out	pipe tside diameter:	3870		m	n					
End of Out Wa	pipe tside diameter : all thickness :	3870 19		m	n					
End of Out Wa Partition :	pipe tside diameter : all thickness :	3870		m	n					
End of Out Wa Partition :	pipe tside diameter : all thickness :	3870 19 10		m	n					
End of Out Wa Partition : Rayleigh dampir	pipe tside diameter : all thickness : ng coefficient :	3870 19 10 0.005		m	n	Number of Reynolds	51	1	4	
End of Out Va Partition : Rayleigh dampin Drag coefficient or tower shadow	pipe tside diameter : all thickness : ng coefficient : v :	3870 19 10 0.005		m	n	Number of Reynold	5 .	1		
End of Out Vartition : Rayleigh dampii Drag coefficient or tower shadow used by aero sc	pipe tside diameter : all thickness : ng coefficient : v : olver only)	3870 19 10 0.005 0		m	n	Number of Reynolds Drag coeff. Reynolds Num	s:	1	•	

Figure 3-6 : Tower setup

### 3.1.5 Nacelle

The Nacelle is a rigid body in DeepLines.

- The tower is clamped to the Nacelle
- The shaft is linked to the Nacelle by pin connections
- The hub is clamped (to avoid convergence issue in static) and may be released using a displacement at the beginning of the dynamic simulation to allow the rotor to rotate (see Figure 3-15).

A box mesh is selected for viewing purposes.

Weight and rotational inertia can be specified, this is the case in this example.

Turbine E	Blade Towe	er Nacelle	Hub Po	wer Train	Control	Aerodyr
Drawing	Fairlead/H	ang-Off poin	nts Physical	Properties	5	
	Nacelle Mass		240.000	t		
		IXX	0.000	kg.m²		
	Nacelle	IYY	0.000	kg.m²		
		IZZ	2607890	ka.m²		

Figure 3-7 : Nacelle mass and inertia setup (see Section 7 for reference frame)

Polar wind coefficients can be added to the Nacelle, this is not the case in this example.

### 3.1.6 Hub

The hub is a rigid body in DeepLines

- The shaft is clamped to the Hub
- The blades are clamped to the Hub

A box mesh is selected for viewing purposes.

Weight and rotational inertia can be specified, this is the case in this example.



Turbine E	Blade Towe	er Nacelle	Hub Po	wer Tr	ain C	ontrol	Aerodyr		
Drawing Fairlead/Hang-Off points Physical Properties									
	Hub Mass		56.800	t	kg.m	2			
		IXX	0.000	kg.m	2				
	Hub Ine	IYY	0.000	kg.m	2				
		IZZ	115926	kg.m	2				

Figure 3-8 : Hub mass and inertia setup (see Section 7 for reference frame)

The reference frame is of the blades (to define twist/pitch) is shown by the hub "fairlead" points where the blades are clamped



Figure 3-9 : Points of connection of the blades to the hub

### 3.1.7 Power train (shafts, gearbox, generator)

The Shaft is composed of three beam elements.

Shaft properties are entered as a common line made of 3 segments (or 4 when HSS is used). A line type is created for the shaft. In this example, low speed shaft (LSS) properties only are specified. HSS is not used.

Default stiffness values are input to make the LSS highly rigid. Default lineic mass is input to make it nearly massless. Default Poisson coefficient value is chosen to make

it not laterally expansible when compressed. Young modulus and specific gravity values are chosen considering the shaft is made of steel.

Outside diameter and wall thickness have generally no influence on the calculations when the mass is negligible and the thickness very high, which is very often the case.

Turbin	e Blade Tov	wer	Nacelle	Hub	Power Tr	ain Control	Aerodynamic	:					
			Length	(m)	Outside	Wall thic	Lineic ma	Axial stiff	Bending	Torsion st	Young m	Poisson c	Spe
	LSS		4.780		0.200	0.002	0.001	1e+11	1e+11	1e+11	210.000	0.0001	7.8
	HSS (option	al)											

Figure 3-10 : Low speed shaft setup

A gear box ratio of 1/97 (<1) is input. This is the ratio between the rotor speed divided by the generator speed.

Gearbox efficiency is taken equal to 1 (default value) meaning there is no power loss.

The Gearbox ratio account for the multiplication factor between the high speed shaft and the low speed shaft.  $Gearbox_{raio} = \frac{LSS \ speed}{HSS \ speed}$ 

The generator inertia is used in idling mode when the rotor is set free to rotate.

Gearbox ratio :	0.010309277835
Generator Inertia :	534.116 kg.m²
	Use table
Gearbox efficiency :	1

Figure 3-11 : Setup of generator and gearbox



Figure 3-12 : Powertrain

### 3.1.8 Control

A dll is selected and a default mode is selected. See 3.4.1 and 3.4.2 for details on control modes and control dll options respectively. These are the default values, but

they may be modified later on by using an EnvironmentSet (see 3.6). It is possible to edit the dll parameters by clicking on the "edit" button.

<ul> <li>○ Control</li> <li>○ Control</li> <li>DII option ControlDI_discon ▼ Edit</li> <li>Mode Production ▼ Edit</li> </ul>	Turbine Blade Towe	er Nacelle Hub	Power Train	Control Aerodynamic
Dll option     ControlDll_discon     Edit       Mode     Production     Edit	C No Control			
	DII option Mode	ControlDII_discon	▼ ▼	Edit

Figure 3-13 : Selection of control dll and mode

### 3.1.9 Aerodynamic

An aero solver is selected. See 3.4.3 for details on aero solver options. It is possible to edit the aero solver parameters by clicking on the "edit" button.

Turbine Blade Tower Nacelle Hub Power Train Control Aerodynamic
C No Aerodynamic loads on blades
Aerodynamic loads on blades (aero solver)
Option AeroBEM_V14  Edit

Figure 3-14 : Selection of aero solver

# 3.2 MODEL COMPONENT: FREING THE HUB

The hub needs to be freed at a beginning of a dynamic part of the simulation otherwise it will not rotate. A displacement (called Free\_hub) of type Dis/connection has been added to the example which releases the HAWT COG. This displacement should then be added in the analyses.

E E	dit displacemer	nt Free_hub					Ed	it displacemen	Free_hub			
Obj	ect:	Free_hub			~	C	)bjec	t .	Free_hub			~
Nar	ne Free_hub				Color	h	lame	e Free_hub				Col
	Name	Object	Location	Туре				Name	Object	Location	Туре	
1	Disp_0	HAWT_Hub	COG	Dis/Connection			1	Disp_0	HAWT_Hub	COG	Dis/Connection	
Prop	erties of selected Name Disp	sub-displacement				Pr	ope N	rties of selected s lame Disp.	sub-displacement			
ę	tatic Dynamic	Reference					Sta	atic Dynamic	Reference			
	Connection/Disc	connection Step	0				- 1	Connection/Disc	onnection Time	0	s	M
	New Connection	Туре	Unchanged	$\sim$			1	New Connection	Туре	Free	$\sim$	н
												V
												н



# Figure 3-15 : Displacement used to release the rotor at the beginning of the dynamic simulation

### 3.3 MODEL COMPONENT: WIND

Different types of wind can be defined. Winds can also be modified in an EnvironmentSet (see 3.6). This example used 3 different types of wind:

 Constant, called Wind\_11ms. The heading and mean velocity are specified then the current speed is constant over height and time. A heading of 180° means that the wind is going towards X negative (DeepLines Global Frame). In this example the blades are facing the wind. This can be checked visually by selecting the wind and turbine in the interface.



Figure 3-16 : Check of turbine and wind orientation with selection of wind and of turbine

 Time series of hub height wind (HH wind), called Wind\_HH. The heading, the location of the wind file, the origin of the wind file wrt to DeepLines Global Frame and the width of the wind field should be specified. A width equal to 0 means the field is infinite. The example is simple, with only horizontal wind speed increasing with time, wind speed constant over height. An example of wind file is shown below.

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!Thi	rust	t cui	rve	for 1	NREL	5MW					
! 8	col	lumns	з:	(1)	Time	•					[s]
!				(2)	Hori	zont	al t	wind s	peed	(V)	[m/s]
!				(3)	Wind	l din	cect:	ion		(Delta)	[deg]
!				(4)	Vert	ical:	L win	nd spe	ed	(VZ)	[m/s]
!				(5)	Hori	zont	al 3	linear	shear	(HLinShr)	[-]
!				(6)	Vert	ical:	L por	wer-la	w shear	(VShr)	[-]
!				(7)	Vert	ical:	l lin	near s	hear	(VLinShr)	[-]
!				(8)	Gust	; (ho	orizo	ontal)	velocity	(VGust)	[m/s]
!											
0	3	0	0	0	0	0	0				
500	3	0	0	0	0	0	0				
600	4	0	0	0	0	0	0				
700	5	0	0	0	0	0	0				
800	6	0	0	0	0	0	0				
900	7	0	0	0	0	0	0				
1000	)	8	0	0	0	0	0	0			

#### Figure 3-17 : HH wind file used in this example

• Time series of full field turbulent wind (FF wind), called Wind\_Turb. The heading, the location of the .wnd wind file, the origin of the wind file wrt to DeepLines Global Frame, time for mirror effect, ramp time duration, beginning of turbulent wind should be specified. The .wnd file is an ASCII file.

Other types of wind are available but have not been used in this example.

### 3.4 WIND TURBINE PROPERTIES

### 3.4.1 Control modes

When defining a Turbine, four types of control can be performed

- Blade Pitch (Displacement)
- Torque on the shaft for power generation (Force)
- Nacelle Yaw (Displacement)
- Brake on the Shaft (Force)

In the example, the generator and pitch control modes are selected in the Production Control Modes. The nacelle yaw control is not selected which means that the turbine is not dynamically controlled in yaw.

# Cut-in and cut-out wind speed are required but not used by the controller used in this example.

The generator-torque control requires the value of rated electric power, a torque rate limit, a minimum and maximum generated torque and generator efficiency. <u>These</u> values – except controller efficiency- are not used with the controller used in this example.

The blade-pitch control requires initial, minimum and maximum pitch values. The pitch control is here the same for the 3 blades (pitch control=collective) and the pitch type is the position.



L TALLS			
📔 Variation tables	Control mode		×
Env tables     Wind turbine properties     Control modes     Production	Control mode	Edit	OK Cancel
Aero solver options	Pitch	Edit	
Wind_11ms Wind_11ms_90 Wind_HH	Yaw	Edit	
Wind_Turb	Brake	Edit	
Sea&Ground	Cut-in wind speed :	3 m/s	
😑 📒 Analysis Sets	Cut-out wind speed :	3 m/s	
Prod_vr     modal_Single     Ø Prod_vr_90	Time step for controler :	2.5e-2 s	

## Figure 3-18 : Setup of control mode

Edit g	enerator control		×	(
⊢Ge	neral			
	<sup>D</sup> ower :	0	W	
1	Max Torque Rate Limit :	0	N.m/s	
1	Min Generated Torque :	0	N.m	
1	Max Generated Torque :	0	N.m	
0	Generator Efficiency :	94.4	% 🔲 Use table	
			OK Cancel	

Figure 3-19 : Setup of generator control

Edit pitch control		×
Initial Pitch :	0	deg.
Min Pitch :	-90	deg.
Max Pitch :	0	] deg.
Min Pitch Rate :	0	deg/s
Max Pitch Rate :	0	deg/s
Time Override :	0	s
Time End Maneuver :	0	- ] s
Pitch End Maneuver :	0	] deg.
Pitch Control	Pitch Type	
Collective	Position	
◯Individual	⊖ Rate	
	OK	Cancel

Figure 3-20 : Setup of pitch control

### 3.4.2 Control dll options

External dll are used to exchange information. In this example, control is applied on blade pitch and generator.

The dll file and DLL procedure name have been specified.

In this example (and this is often the case), the reference frame is defined by the mean wind direction.

■   <mark>       </mark>	Control dll option	∟₀ !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!	×
Control modes	DLL file	_\00_CONTROL\Discon.dll OK	
Control dll options Control dll options Generation Control Dll_discon Generations	DLL procedure name	DISCON Cance	3
Model     Wind_11ms     Wind_11ms_90     Wind_HH			
a wind_Turb a v Free_hub a v Parked	Data exchange options Reference frame Mean wind		
■ DLCprod     ■ DLCprod     ■ DLCprod     ■ DLCprode     ■ DLCprode     ■ V→ HAWT     ■ V→ HAWT_Blade_1	O Nacelle		





#### 3.4.3 Aero solver options

An XML file for aerodynamic option could have been generated by ticking the available options. In this case, the .xml was already available and its location has been indicated.

Blade profiles have been fully defined so there is no need to load an XML file for blade profiles.

	Aero solver option			~
🖮 📄 Aero solver options				<u>^</u>
AeroBEM_V14	Generate XML file for aerodynamic option			OK
Model				
Wind_11ms	Prandtl's correction for tip losses		Save as	Cancel
₽ 🔜 Wind_11ms_90 -₽ 📑 Wind HH	Prandtl's correction for hub losses			
- I I I I I I I I I I I I I I I I I I I	Tower shadow model (effects of the to	ower on the wind)		
	Dynamic stall model			
-₽ E DLCprod -₽ E DLCparked	Model for dynamic inflow			
⊨ I I I I I I I I I I I I I I I I I I I	Correction for skewed wake (yawed n	otor)		
HAWT_Blade_2	Snel's correction for three dimensione	al and rotation effects		
HAWT_Tower	XML file for aerodynamic option			
→ HAWT_Hub → HAWT_Shaft	Aero models XML\00-AERO\aeroBEM_	V14xml		
Sea&Ground	While file for blacker profiles (providual providers	-		
Analysis Sets	AML file for plades profiles (previous versions	»)		
e- 📟 Default	Blade XML			

Figure 3-22 : Generation or selection of XML file for aerodynamic option and if necessary for blade profiles

## 3.5 DRAG/LIFT DATABASE: FOIL PROFILES

Each blade section is associated with a profile. Each profile type is defined in the drag/lift database. Values are not depending on Reynolds number in this example. The lift, drag and moment coefficients have been specified for attack angle between -180° and +180°. Attack angle is shown in Figure 3-24.

••••••••••••••••••••••••••••••••••••••	Edit foil profile	le .				
Line types     Floater motion types     Contact types     Buovancy module types	Type: C Name: C	ylinder2 ylinder2		New		]
Steady internal fluids     Variable internal fluids     External fluids     Ballast properties     Link properties     Marine Growth	Options Use stall e Thickness Reynold's num	effect	1.000	Fully separated flow	w 0	deg 1/rad
Drag/Lift database	Number:		Attack Angle (	Lift coeff (-)	Drag coeff (-)	Moment coeff
Cylinder1	Insert	Derete	-180.0000	0.0000	0.5000	0.0000
	Reyno	ld's	0.0000	0.0000	0.5000	0.0000
	1 1.000		180.0000	0.0000	0.5000	0.0000

Figure 3-23 : Foil profile definition in drag/lift database





Figure 3-24 : Attack angle  $\alpha$ : angle between incident flow and blade reference frame

### 3.6 ENVIRONMENT SET

Environment sets can be used to run an analysis set containing different wind files or control strategy.



Figure 3-25 : Environment set toolbar button (in red square)



	Edit er	vironment set DLCp	rod										×
0	oject:	DLCprod				`	~						OK
													Save
Na	me	DLCprod											Cancel
	General	Combination matrix	Winds Turbines										
		Number of turbines pro	operties: 2	•		l	Insert new turbine prop	pe	erties				
					Re	em	iove selected turbines	р	roperties				
		•			o			Т					
	1	TurbineProd	Hawt	-	Start Up	-	Start Up var table	1	Production	-	Control options Aerodynamic so	→ →	
	2	TurbineParked	HAWT	-	None		Default	1	Default	-	ControlDII_par Default	-	
											_, _,		
												-	

Figure 3-26 : Example of turbine options in an Environment Set



## 4 STARTUP

The startup of the turbine can be modelled using:

- a variation table (single analysis) and in addition for an analysis set an environment table which can be selected in the model browser (Figure 4-1),
- a displacement.



#### Figure 4-1 : Variation tables and environment tables in the model browser

### 4.1 SINGLE ANALYSIS

The variation table for start-up (Figure 4-2) should have 2 columns and at least 2 lines. The first one is filled with time (in s) and the second one with rotor velocity (in rad/s). In this example, the rotor velocity increases between 0 and -1.26 <u>rad/s</u> (=12 rpm) during the first 100s of the dynamic simulation. Velocity is negative to obtain a clockwise rotation of the rotor.



bject	Start12rpm_10	Os	~	•				0	ĸ
ame	Start12rpm_10	0s						Car	icel
ows nu	mber 2	\$	Colur	nns number	2				
Name		×			v	_	_	Selected	i row(s) :
1	0	10	0		,			Del	ete
2	100		-1.2	6				Insert	t after
								Del	ete
								Insert	t after
0.00						 1		Insert	aph
0.00								Insert	aph
0.00								Gre	aph
0.00								Gra	aph
0.00 0.20 0.40 0.80 1.00								Gre	sph
0.00 0.00 0.40 0.60 0.80 1.00 1.20 0.80 0.80 0.80 0.80 0.80 0.80 0.80 0								Gra	aph

Figure 4-2 : Example of variation table.

A displacement is used to impose the rotor velocity defined previously in the variation table. The displacement is imposed on the Hub and is of type "Control". The type "Turbine start up" is selected in the relevant tab. The variation table is selected in the "prescribed speed" tab. "End of start up" is used to specify at which time the startup control is released and the turbine control is taking over. This value should be taken into account when setting up the time in the variation table.

The displacement should be added in the analysis (see Figure 4-4). The analysis is ready to be run.



Object	DispStartup_100	s		~			OK
Name Disp	Startup_100s			Color	-		Save
			-	_	_		Cance
Name	Object	Location	Type	<u> </u>	Objec	HAWT	
1 StartUp	HAWI_Hub	COG	Control		Locati	on HUB ref point ~	
					Туре	Incremental ~	
						Create new displacement	
						Remove selected displacement	
Properties of se	ected sub-displacement		-			Remove selected displacement	
Properties of se Name	ected sub-displacement StartUp					Remove selected displacement	
roperties of se Name Type	ected sub-displacement StartUp Turbine start up			~		Remove selected displacement	
roperties of se Name Type Proportiona	ected sub-displacement StartUp Turbine start up term 1.000e+00	o 3 N.m/(rad/	s)	v		Remove selected displacement	
Yroperties of se Name Type Proportiona Derivative te	ected sub-displacement StartUp Turbine start up term 1.000e+00 rm 0.000e+00	9 3 N.m/(rad/ 0 N.m/(rad/	s) 5 <sup>9</sup> )	×		Remove selected displacement	
Properties of se Name Type Proportiona Derivative tr Integral term	ected sub-displacement StartUp Turbine start up term 1.000e+00 1.000e+00 1.000e+00	0 3 N.m/(rad/ 3 N.m/(rad/ 3 N.m/rad	s) 5 <sup>9</sup> )	~ Prescribed speed		Remove selected displacement	
Properties of se Name Type Proportiona Derivative tr Integral term Comer freq	ected sub-displacement StartUp Turbine start up term 1.000e+00 1.000e+00 1.000e+00 1.570796	0 3 N.m/(rad/ 3 N.m/(rad 4 1 1 1 1 1 1 1 1 1 1 1 1 1	s) s*)	Prescribed speed Variation table	Start12rpm_100s	Remove selected displacement	
Properties of se Name Type Proportiona Derivative tr Integral term Comer freq Maximum to	ected sub-displacement StartUp Turbine start up term 1.000e+00 1.000e+00 1.000e+00 1.000e+00 1.570796 rque 1.000e+10	0 3 N.m/(rad/ 3 N.m/(rad/ 3 N.m/rad Hz 1 Hz	s) s <sup>a</sup> )	Yrescribed speed Variation table	Start12rpm_100s	Remove selected displacement	
Properties of se Name Type Proportiona Derivative tr Integral term Comer treq Maximum to Maximum to	ected sub-displacement StartUp Turbine start up term 1.000e+00 irm 0.000e+00 1.000e+00 1.000e+00 inn 1.000e+00 1.570796 rque 1.000e+10 rque rate 1.000e+10	0 N.m/(rad/ 0 N.m/(rad/ 3 N.m/rad 3 N.m/rad Hz 0 N.m 0 N.m/s	s) 5 <sup>9</sup> )	Prescribed speed Variation table	Start12rpm_100s	Remove selected displacement	









## 4.2 ANALYSIS SET

Startup can be done in an AnalysisSet with varying parameters depending on the analysis. The same setup than for a single analysis should be used. In addition, an environment table and environment set should be defined.

The environment table has 3 columns (see Figure 4-5).

- Index of the analysis in the analysis set. In this example, the first line corresponds to the last analysis of the analysis set. The environment table should have an index for each of the analysis in the analysis set. In this example there is 7 analyses in the analysis set. There should not be twice the same index in the first column of the environment table.
- Time in s. End of startup control time is the same for all the analysis in the environment set.

So for example, for the 4<sup>th</sup> analysis in this analysis set, the rotor velocity of - 1.26 rad/s is achieved at 80s then the turbine control starts at 100s.

For the 5<sup>th</sup> analysis, a rotor velocity of approx. -1.26 rad/s is achieved at 100s then the turbine control starts (the velocity of -1.51 rad/s is not achieved).

• Rotor velocity in rad/s

bject	EnvStartUp	~	
lame	EnvStartUp		
lows nu	mber 7	Column	s number 3
Name	col1	col2	col3
1	7	110	0
2	2	95	0
3	3	80	-0.89
4	4	80	-1.26
5	5	120	-1.51
6	6	80	-1.26

# Figure 4-5 : Environment table used in combination with environment set for turbine startup

An environment set is defined. In the turbine sheet:

- The turbine "HAWT" is selected
- The displacement "StartUp" is selected.
- The environment table "EnvStartUp" is selected in the var table sheet.
- Control mode, options and aerodynamics are selected to have the production behaviour of the turbine.

Then an analysis is created using this environment set.



	Edit e	environment set [	DLC_example_star	rtup					
0	bject:	DL	C_example_startup	Ι		$\sim$			
Νa	ame Gener:	DLC_exe	ample_startup atrix Winds Turb	ines					
		Number of	turbines properties	s: 1		Insert new t	urbine properties		
						Remove selecte	ed turbines properti	es	
		Name	Hawt	Start Up	Start Up var t	Control mode	Control optio	Aerodynamic	
	1	TurbineProd	HAWT -	StartUp 💌	EnvStartUp 💌	Production 💌	ControlDII 💌	AeroBEM 💌	

Figure 4-6 : Environment set Turbine setup with startup

🛛 Edît e	nvironment set DLC	exampl	e_startup	
Object	DLC_ex	ample_s	×	
lame	DLC_exampl	e_startup		
Genera	General Combination matrix		Turbines	
Num	per of environments	7		EX
	Name		Winds	Turbine
1	above_cutout		wind_above_cutout	TurbineProd
2	cutin		wind_cutin	TurbineProd
3	below_rated		wind_below_rated	TurbineProd
4	rated		wind_rated	TurbineProd
5	above_rated		wind_above_rated	TurbineProd
6	cutout		wind_cutout	TurbineProd
7	below_cutin		wind_below_cutin	TurbineProd

Figure 4-7 : Environment set combination matrix with startup



## 5 **RESULTS**

Analyses are described in detail in the following section. The available results are presented in this section.

# 5.1 WIND, ROTOR AND GENERATOR

Specific turbine results can be accessed by selecting the Nacelle then diagnostics. (see Figure 5-1). Data are also saved in the Turbine and Rotor files. In this example, these files are called turbine\_HAWT.txt and rotor\_HAWT.txt and are available in the analysis folder.

A list of specific turbine results is provided in table below. Attention must be paid to the units of the output results.

	File	Unit	Definition
L.speed		rpm	Low speed shaft speed
H.speed		rpm	High speed shaft speed (LSS times the gear box ratio)
Pitch		0	Blade pitch angle modified by the controller
Gen.Torque		N.m	Generator torque
Elec.Power		Watt	Electrical power output of the generator
Azimuth	turbine	0	Blade 1 angular position during rotation from 0 to 180°.
OPDeflect		m	Out-of-plane and in-plane tip deflections of Blade 1
IPDeflect		m	relative to the undeflected blade-pitch axis
VelX		m/s	
VelY		m/s	Absolute velocity of wind in global frame
VelZ		m/s	
Rotation		0	Blade tip rotation about blade axis
Rot.Vel.		°/s	Rotational velocity of rotor
Thrust	rotor	Ν	Thrust force generated by the rotor
Moment		N.m	Moment generated by the rotor

Table 5-1 : Turbine results available in DeepLines WIND



Figure 5-1 : Selection of turbine results



# 6 ANALYSES AND ANALYSIS SETS

### 6.1 **RUNNING AN ANALYSIS**

When the first analysis is run,

- Two JSON files named *HAWT\_1.JSON* and *HAWT\_1\_Blade.JSON* are created into the AERO directory.
- HAWT.JSON contains data about the hub, the tower and the nacelle;
- HAWT\_Blade.JSON contains data about the blades.

When an analysis is run, in addition to the typical analysis files, a turbine and a rotor files are created in the analysis folder.

### 6.2 PROD\_VR

This simulation is run with a constant wind speed of 11.4 m/s (rated wind speed) (see VeIX plot).

The electrical power obtained once the turbine shows a steady behaviour. The electrical power is slightly below the rated power (5 MW).



Figure 6-1 : PROD\_VR results

# 6.3 **PROD\_VR\_90**

This is the same case than the previous one but the wind has been rotated by 90°. The turbine is rotated by 90° during the static calculation with the Displacement Yaw90. Results are similar to Prod\_vr results.



### 6.4 **PROD\_VR\_HH**

This simulation is similar to prod\_vr (6.2) but with a time series of wind instead of a constant wind.

In this example, the wind speed is slowly increasing from 3 to 25 m/s. Wind is constant over height, without turbulence, and is facing the turbine.

Blade pitch angle varies during the simulation. The electrical power reaches its rated value when the wind speed (velX) reaches it rated value. The thrust increases until the wind speed reaches it rated value then the blade pitch angle changes and the thrust decreases.



Figure 6-2 : PROD\_VR\_90 results



### 6.5 **PROD\_VR\_TURB**

This simulation is similar to prod\_vr (5.2) but with a turbulent time series of wind instead of a constant wind.

In this example, the wind speed is varying around the rated speed. Wind is constant over height and is facing the turbine.

During the start of the turbine, the shaft speed, electrical power and thrust are increasing until stabilising (but still varying). The blades could have pitched if required but this was not the case here.



Figure 6-3 : PROD\_VR\_TURB results



## 6.6 PROD\_VR\_STARTUP\_80S, 100S AND 120S

This simulation is run with a constant wind speed of 11 m/s slightly below the rated wind speed (11.4 m/s). Startup is applied in the variation tables during the first 80, 100 or 120 s of the simulation. The variation table has 2 columns and at least 2 lines:

- First column: time in s
- Second column: rotation speed in rad/s. Please note the negative sign for a clockwise rotation.

A rotor speed of approx. 12 rpm should be achieved at 100 s in all cases, and even before (at 80s) for the 80s case. The startup control is turn off at 100s. Results are similar for the 100 and 120 s case.



Variation table max time

Figure 6-4 : PROD\_VR\_STARTUP\_80S, 100S AND 120S results

# 6.7 **PROD\_VR\_STARTUP\_X**

This simulation is the same than PROD\_VR\_STARTUP\_100S but the setup is done in a different way, using a new feature. This new feature is particularly useful during the building and testing of the model. In calculation parameters, the new sheet "HAWT properties" has been used and filled as follow:

Analysis Type   F Select the H	loater Motion   Lines	s Properties   Contact	ts   Wave shift	Numerical parame	aters Pretensions	: / Initial angles	Cance HAWT Properties
Analysis Type   F Select the H	loater Motion Lines	s Properties   Contact	ts   Wave shift	Numerical parame	eters   Pretensions	: / Initial angles	HAWT Properties
Select the H	HAWT properties to b	he used for this analys	sis:				
			1				
Hawt	Start up	Start up var	Yaw	Yaw var table	Control mode	Control options	Aerodynamic
1 HAWT	StartUp100s	s 💌 Start12rp 💌	None 💽	🛛 Default 🔄 🚬	Default 🔄 🚬	Default 📃 💌	Default 🔄

Figure 6-5 : Setup for startup in calculation parameters

Start up has been defined in a displacement and start up variable in a variation table as shown below. The start up variable could also have been set to "default" which would have automatically selected "Start12rpm\_100s".

💷 Ec	dit d	lisplacement DispSt	artup_100s								
ОЫ	ject:	DispSta	rtup_100s			•					
Na	me	DispStartup_100s	]			Color		·]			
	I	Name	Object		Location	Туре		Í.			
1	2	5tartUp100s	HAWT_Hub		COG	Control	1				
Edi	it ¥ar	riation table					×	<ul> <li>I</li> </ul>			
Obje	ect	Start12rpm_100s	-				ОК				
Nam Row	Name     Start12rpm_100s     Cancel       Rows number     2     2										
Nar	me	×			У		Selected row(s):				
1		0		0			Delete				
2	_	100		-1.26			Insert after				
							msert arter				

Figure 6-6 : Location of properties used in calculation parameters for startup

# 6.8 **PROD\_VR\_90\_X**

This simulation is the same than PROD\_VR\_90 but the setup is done in a different way, using a new feature to rotate the turbine in yaw during static. This new feature

is particularly useful during the building and testing of the model. In calculation parameters, the new sheet "HAWT properties" has been used and filled as follow:

Analysis Type       Floater Motion       Lines Properties       Contacts       Wave shift       Numerical parameters       Pretensions / Initial angles       HAWT Properties         Select the HAWT properties to be used for this analysis:		ulation para	ameters of Pro	)d_\	n_90_x							Πκ
Analysis Type       Floater Motion       Lines Properties       Contacts       Wave shift       Numerical parameters       Pretensions / Initial angles       HAWT Properties         Select the HAWT properties to be used for this analysis:												Cancel
Analysis Type       Floater Motion       Lines Properties       Contacts       Wave shift       Numerical parameters       Pretensions / Initial angles       HAWT Properties         Select the HAWT properties to be used for this analysis:												
Select the HAWT properties to be used for this analysis:         Hawt       Start up         Start up       Start up var         Yaw var table       Control mode         Control options       Aerodynamic         HAWT       None         Default       Default	Analysi	s Type Float	er Motion Line:	s Pro	perties Cont	act	s   Wave shif	t   1	Numerical parame	eters Pretensions	: / Initial angles	HAWT Properties
Select the HAWT properties to be used for this analysis:         Hawt       Start up       Start up var       Yaw       Yaw var table       Control mode       Control options       Aerodynamic         1       HAWT       None       Var yaw90_0       Default       Default       Default       Default       Default       Var yaw90_0												
Hawt       Start up       Start up var       Yaw       Yaw var table       Control mode       Control options       Aerodynamic         1       HAWT       None <ul> <li>Default</li> <li>Yaw90_0</li> <li>Default</li> <li>De</li></ul>	S	elect the HAV	VT properties to t	oe u:	sed for this ana	alys	is:					
Hawt       Start up       Start up var       Yaw       Yaw var table       Control mode       Control options       Aerodynamic         1       HAWT       None       ✓       Default       ✓												
Hawt         Start up         Start up var Yaw         Yaw var table         Control mode         Control options         Aerodynamic           1         HAWT         None         T         Default         T         T         Default												
1 HAWI None Derault Yawyu_U Derault Derault Derault Derault		Hawt	Start up	-	Start up var		Yaw Yawaa o	-	Yaw var table			Aerodynamic
			None		Derault		1 xawao_o					
	1											
	1	-										

Figure 6-7 : Setup for initial yaw in calculation parameters

Yaw is defined in a displacement. The sub-displacement "Yaw90\_0" is input in the setup showed above.

displacer	acement Yaw90			
ot:	Yaw90		•	
e <mark>Yaw90</mark>	aw90		Color	
Name	e Object	Location	Туре	
Yaw90_0	0_0 HAWT_Nacel	le COG	Control	
Yaw90_0	0_0 HAWT_Nacel	le COG	Control	

Figure 6-8 : Setup for initial yaw in calculation parameters

## 6.9 **PROD\_VR\_90\_X\_1**

This simulation is the same than PROD\_VR\_90 and PROD\_VR\_90\_X but the setup is done in a different way, using a new feature, to rotate in yaw the turbine during static. This new feature is particularly useful during the building and testing of the model. In calculation parameters, the new sheet "HAWT properties" has been used and filled as follow:



Editi	ing calc	culation param	eters of Prod	_vr_90_x	:_1							×
												OK Cancel
	Analysi	is Type Floater	Motion Lines P	roperties	Contacts	Wave shift	Numerical	parame	ters Pretensio	ns / Initial angles	HAWT P	Properties
	s	Select the HAWT	properties to be	used for th	nis analysis	к 						
		Hawt	Start up	Start up	pvar	Yaw	Yaw var	table	Control mode	Control option	Aerodyr	namic
	1	HAWI	None	Default		Yaw90_0 _	yaw_18		Default	Default	Default	
		💼 Ec	lit Variation t	able								
		Obje	oct yaw_180	)			$\sim$					

Name	yaw_180					
Rows nu	mber 1 🜩	Columns number 3				
Name	x	У	Z			
1	0	180	180			

# Figure 6-9 : Setup for rotation in yaw of the turbine during static in calculation parameters

The yaw variation table format should be 1 line with 3 columns:

- Initial step
- Final step
- Variation

In this case, results are similar than if the "yaw var table" parameter was using the default value, because 90 static steps are used. The yaw var table can be used to define different static angles.

## 6.10 PARKED\_X

This simulation is the same than DLC\_parked\_parked, PROD\_VR\_90 or PROD\_VR\_90\_X but the setup is done in a different way, using a new feature. This new feature is particularly useful during the building and testing of the model. In calculation parameters, the new sheet "HAWT properties" has been used and filled as follow:



diting calc	ulation parame	eters of Parke	:d_x						×
								OK Cancel	
Analysi: S	s Type Floater M elect the HAWT p	totion Lines P properties to be	roperties Contac used for this analy	its   Wave shift     sis:	Numerical parame	ters Pretensions	s / Initial angles	HAWT Properties	
	Hawt	Start up	Start up var	Yaw	Yaw var table	Control mode	Control options	Aerodynamic	
1	HAWT	None	Default 💽	None 💌	Default 💌	Default 💌	ControlDll 💌	Default 💌	

Figure 6-10 : Setup for parked in calculation parameters

Production		
🔤 🔅 Parked	Control dll option	×
🖃 Control dll options		
ControlDll_discon	DLL file\00_CONTROL\nocont.dll	
ControlDIl_parked     Aero solver options	DLL procedure name NOCONT	Cancel
- Model	Input files for dll : Add Remove	9
Wind_11ms		-
🛛 🗹 Free hub	Data exchange options	

Figure 6-11 : Setup for control options in calculation parameters

# 6.11 MODAL\_GLOBAL

This is a modal analysis with the whole turbine. Results are similar to typical modal analysis.



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### Figure 6-12 : View of dss of modal analysis

## 6.12 DLC\_EXAMPLE

This is an analysis set with different production cases with wind speed varying from 2 to 30 m/s depending on the case. Wind speed is constant over time and height. A case (fixed) is also present in this analysis set for a case without control. However, the blades are not rotated by 90° to reduce thrust forces and therefore this is not a real parked case. See 6.13 for a parked case.

Some results are shown below.







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## 6.13 DLC\_PARKED

The blades are rotated by a 90° angle during the static calculation in order to reduce the drag forces on them and consequently the thrust force. The hub is not released at the beginning of dynamic calculation. A dummy controller is used which does nothing. A DLC has been used to modify the parameter of the controller for this analysis only.



Figure 6-14 : DLC\_parked results

# 6.14 DLC\_EXAMPLE\_STARTUP

This is an analysis set with different production cases with wind speed varying from 2 to 30 m/s depending on the case. Wind speed is constant over time and height. Startup is applied to all cases with different parameters.

#### Below cutin







Figure 6-15 : DLC\_example\_startup results



# 7 APPENDIX: CONVENTIONS FOR HAWT

This section presents the conventions for HAWT.

## 7.1 COORDINATE SYSTEMS FOR HAWT

- Global coordinate system (G) : DeepLines global coordinate system
  - Origin : global frame origin,
  - $\circ$  X<sub>G</sub>: pointing to user required horizontal direction,
  - $\circ$  Y<sub>G</sub> : (X<sub>G</sub>,Y<sub>G</sub>,Z<sub>G</sub>) direct coordinate system,
  - Z<sub>G</sub> : pointing vertically upward opposite to gravity.
- Nacelle coordinate system (N)
  - o Origin : rigid body reference point, top of the tower,
  - $\circ$  X<sub>N</sub> : defined by the heading of the turbine or by the heading (azimuth) of the fairlead point on which the turbine is connected,
  - $\circ$  Y<sub>N</sub> : (X<sub>N</sub>, Y<sub>N</sub>, Z<sub>N</sub>) direct coordinate system,
  - $\circ$  Z<sub>N</sub>: pointing vertically upward opposite to gravity.
- Hub coordinate system (H)
  - o Origin : rigid body reference point; defined on the Nacelle as "Rotor Reference,"
  - $\circ$  X<sub>H</sub>: downward (shaft tilt from vertical direction),
  - $\circ$  Y<sub>H</sub> : (X<sub>H</sub>, Y<sub>H</sub>, Z<sub>H</sub>) direct coordinate system,
  - $\circ$  Z<sub>H</sub> : hub rotation, upwind with shaft tilt from horizontal.



Figure 7-1 : Coordinate systems for HAWT: global, nacelle and hub

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In the hub local frame, the blades initial pitch orientation is entered by the user. In most cases, it is defined in "production mode" where the pitch is closed to 0° as opposed to the "feathered mode" where the pitch is closed to -90°. In the following schematic, the blades are presented in production mode (No Tilt of the shaft)



Figure 7-2 : Coordinate hub local frame



- Coned coordinate system (CO)
  - Oriented by the blade fairleads of the hub.
  - $\circ$  X<sub>CO</sub> : in the (Y<sub>H</sub>, Z<sub>H</sub>) plane.
  - o Y<sub>CO</sub> : (X<sub>CO</sub>, Y<sub>CO</sub>, Z<sub>CO</sub>) direct coordinate system,
  - $\circ$  Z<sub>co</sub>: in the blade axis at connection.

The Coned coordinate system is represented below. This frame of reference is fixed with respect to the hub. Note that in the frame below, the blade is represented in feathered mode.

The structural twist (elasticity), aerodynamic pitch (aerodynamics) and mass axis orientation (inertia) are defined in this frame.



Figure 7-3 : Coned coordinate system



# 7.2 **PROFILE PROPERTIES**

A profile is defined by:

- A reference point P defined by the beam finite element in DeepLines (reference point of the Mechanical Blade coordinate system). The structural twist provides the rotation around the blade axis in the Blade coordinate system. Stiffness and inertia are defined in this reference system.
- The aerodynamic center position (x and y coordinate) and the CoG position (x and y coordinate) are defined in the in the Mechanical Blade (MB) frame (red frame blow)



Figure 7-4 : Aerodynamic center position and COG in MB frame

• The aerodynamic pitch defines the direction for the aerodynamic loads (see section 7.3)



Figure 7-5 : Aerodynamic pitch



Notes:

- The three nodes are at the same location unless COG and the AeroCenter locations are defined in the local frame of the blade section. To do so, their X and Y local coordinates shall be introduced (in meters) in the blade definition panel.
- Mechanical stiffness's are applied on the beam element point; no modification is introduced due to local (X, Y) coordinates of the COG. These local (X, Y) coordinates of the COG are used to calculate the moment due to the section weight to be applied on the beam point.

## 7.3 PITCH ANGLE AND ATTACK ANGLE

The aerodynamic center is defined in the profile properties. The orientation of the Aerodynamic Blade frame may be different from the Mechanical Blade Frame. Therefore the aerodynamic pitch is defined for each section in the Blade coordinate system. If the aerodynamic pitch is equal to the structural twist, the Mechanical Blade and Aerodynamic Blade frames are the same.

- The Aerodynamic reference frame orientation is defined at the beginning of the calculations based on the aerodynamic pitch provided as input.
- An initial pitch may be added (see control definition panel > pitch > initial pitch);
- During the simulation, the pitch instruction from the controller is applied to the root of the blade and the blade torsion stiffness propagates it along the blade.





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The combination of the wind speed and the local blade speed due to the turbine rotation generates an incident flow with an attack angle  $\alpha$  with respect to the blade reference frame.



Figure 7-7 : Attack angle

The aerodynamic forces are derived from the attack angle and the polar coefficients associated with a profile.

# 7.4 COUPLING BETWEEN THE MECHANICAL AND AERODYNAMIC MODEL

All exchanges between DeepLines and the Aerodynamic solver are done in the global reference frame, which means at each time step:

- DeepLines provides to the aerodynamic library the positions, the velocities, the wind speed as well as the blade local axes vectors in the global frame; *NB: These data are provided at the mechanical center P.*
- The aerodynamic library provides the aerodynamic forces and moments in the global frame. These efforts are derived from the attack angle, the relative velocities and the profile aerodynamic properties; *NB: The efforts are calculated at the Aerocenter.*
- In DeepLines, the local (X, Y) coordinates of the Aerocenter are used to derive the moment of the aerodynamic forces, calculated by the aerodynamic solver, to be applied on the beam point P. This moment is superimposed to the aerodynamic moment calculated with the *C*<sub>m</sub> coefficient.



## 7.5 TURBULENT WINDS

Turbulent winds may be defined in specific files. At each time step, wind speeds are interpolated from the defined grids.



Figure 7-8 : Example of turbulent wind grid

These grids shall be previously generated with external software.

- The wind is defined by the keyword \*WINDFILE (see keywords manual). A reference point as well as an heading angle may be defined to introduce the wind grids into the general DeepLines model in terms of (X,Y) and wind direction.
- These wind grids are fixed. They are not moving with the turbine. At each time step, the updated positions of any point of the model are used to interpolate the wind speed at that point.