Evaluation Report

Design Codes FAST and ADAMS® for Load Calculations of Onshore Wind Turbines

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1 Documentation

1.1 Documentation examined

1.1.1 UAE-stall-turbine time series of extreme load case "Vacuum Rigid", FAST and ADAMS output files, dated 12-11-2004.

1.1.2 UAE-stall-turbine time series of extreme load case "Yaw Rate Vacuum", FAST and ADAMS output files, dated 02-12-2004.

1.1.3 UAE-stall-turbine time series of extreme load case "Fixed Yaw Rotating", FAST and ADAMS output files, dated 09-12-2004.

1.1.4 UAE-stall-turbine time series of extreme load case "Abrupt wind Drop", FAST and ADAMS output files, dated 07-12-2004.

1.1.5 UAE-stall-turbine time series of extreme load case "Unsheared Gust", FAST and ADAMS output files, dated 10-12-2004.

1.1.6 UAE-stall-turbine time series of fatigue load cases "Turbulent Power Curve", FAST and ADAMS output files, dated 19-01-2005.

1.1.7 UAE-stall-turbine fatigue analysis "Turbulent Cumulative Spectra", FAST and ADAMS simulation result, dated 07-02-2005.

1.1.8 UAE-stall-turbine fatigue analysis "Damage Equivalent Loads (DEL)", FAST and ADAMS simulation result, dated 07-02-2005.

1.1.9 WindPact1.5 time series of extreme load case "Yaw Rate Vacuum", FAST and ADAMS output files, dated 02-12-2004.

1.1.10 WindPact1.5 time series of extreme load case "Fixed Yaw Rotating", FAST and ADAMS output files, dated 09-12-2004.

1.1.11 WindPact1.5 time series of extreme load case "Abrupt wind Drop", FAST and ADAMS output files, dated 07-12-2004.

1.1.12 WindPact1.5 time series of extreme load case "Unsheared Gust", FAST and ADAMS output files, dated 10-12-2004.

1.1.13 WindPact1.5 time series of fatigue load cases "Turbulent Power Curve", FAST and ADAMS output files, dated 07-03-2005.

1.1.14 WindPact1.5 fatigue analysis "Turbulent Cumulative Spectra", FAST and ADAMS simulation result, dated 07-03-2005.

1.1.15 WindPact1.5 fatigue analysis "Damage Equivalent Loads (DEL)", FAST and ADAMS simulation result, dated 07-03-2005.

1.2 Documentation noted

1.2.1 "FAST User's Guide", NREL technical report No. NREL/EL-500-29798, version 5.0, dated March 2004, 95 pages.

1.2.2 "Wind Turbine Design Codes: A Preliminary Comparison of the Aerodynamics", NREL technical report No. NREL/CP-500-23975, dated December 1997, 10 pages.

1.2.3 "FAST_AD Code Verification: A Comparison to ADAMS", NREL technical report No. NREL/CP-500-28848, dated January 2001, 10 pages.

1.2.4 "Design of a Tapered and Twisted Blade for the NREL Combined Experiment Rotor", NREL technical report No. NREL/SR-500-26173, dated March 1999, 23 pages.

1.2.5 "Basic Machine Parameters", NREL UAE-stall-turbine description, dated April 2004, 21 pages.

1.2.6 "Test13.fst / Test13_AD.ipt", WindPact1.5 model parameters and FAST input files, dated October 2004.

1.2.7 UAE-stall-turbine fatigue analysis "Probability Mass Function (PMF)", FAST and ADAMS simulation result, dated 21-01-2005.

1.2.8 WindPact1.5-turbine fatigue analysis "Probability Mass Function (PMF)", FAST and ADAMS simulation result, dated 24-01-2005.

1.2.9 "WindPACT Turbine Design Scaling Studies", NREL Subcontractor Report No. NREL/SR-500-29492, April 2001.

2 Scope

Evaluation of the design codes FAST of NREL and ADAMS® of MSC.Software[1] (NREL adapted ADAMS for modeling HAWTs by linking it with NREL's AeroDyn subroutine) by calculations results load predictions for different wind turbine types with the Germanischer Lloyd WindEnergie (GL Wind) in-house tool DHAT.

3 Extent of examination

The comparison of the loads was carried out for two different simulation codes FAST and ADAMS. As reference, the loads calculated with the GL Wind in-house code DHAT were applied. A set of special load cases have been defined to achieve detailed information on load origins such as aerodynamic loads, mass and inertia loads and dynamic loads from elastic structural responses. For the comparison of fatigue loads, the conditions of the GL class II-A according to the "Guidelines for the Certification of Wind Turbines," GL Wind, edition 2003 and supplement 2004, have been applied. In order to reduce the amount of data, a list of representative sections and simulation parameters has been defined. This list contains 40 output channels and can be found in Annex B. The load assumptions generated by FAST and ADAMS have been examined for completeness and are confirmed for

[1] „ADAMS" is used to imply „ADAMS®" throughout this document

the load conditions by computations carried out in parallel by GL Wind. Load deviations found are within the technical tolerance limits. The masses, mass moments of inertia, distances between centers of gravity, structural and aerodynamic profile data as indicated have been checked for plausibility and have been used identically for the involved simulation codes. Pre- and post-processing tools accompanying the two software packages have not been assessed within this study.

4 Remarks on examination

4.1 Prerequisites

The comparison comprised two different turbine types. The first turbine model was a two-bladed stall turbine with about 11 kW rated power. The rotor was placed in the upwind position and had a fixed teeter hinge. The blades used with S809 airfoils. This turbine was used in several NREL research projects, e.g. in the Unsteady Aerodynamics Experiment (UAE), and a lot of load and aerodynamic measurement data is available. The aerodynamic measurements made in the AMES full size wind tunnel contribute especially suitable background information to confirm the plausibility of simulated results.

The second turbine used for simulations was a typical three-bladed, variable-speed upwind turbine with active yaw. Power and rotor-speed control is achieved by pitch adjustment and torque control. With a rated power of 1.5 MW this turbine represents common technology and the state of the art for the current wind turbine market. However, this turbine is a virtual model which was developed in the scope of an NREL research project, see 1.2.9. The rotor blade used S818, S825, and S826 airfoils.

NREL generated and calculated the input files and corresponding time series of the FAST and ADAMS simulations and submitted these to GL Wind. The input files containing the turbine model and the load case definitions have been checked for plausibility. GL wind calculated in parallel loads with their in-house code DHAT (Dynamic Horizontal Axis wind turbines in Turbulent flow), which were used for comparison.

The FAST code (Fatigue, Aerodynamics, Structures and Turbulence) is an open-source calculation tool which was constantly enhanced by NREL over the last decade. The aerodynamic forces are calculated with the included module AeroDyn. It generates time series in the time domain taking into account the system behavior and the complete structural dynamics. The FAST code is able to model teeter hinges, passive yaw wind vanes and down wind operation. The current version of FAST does not consider the drag forces on hub and nacelle. However, in the scope of the further development of FAST this feature will be included in the following versions. For modeling a pitch controlled turbine, a separate controller module has to be linked to the FAST program. For the comparison of the WindPACT 1.5 turbine a FORTRAN-based controller code generated by NREL has been linked to FAST interface to take into account the variable speed control characteristics in the load calculations. Extreme value analysis, Rainflow count analysis or output of component related eigenfrequencies are not included in the current version. For post-processing of the calculated time series, external tools have to be used.

The second simulation tool used is the wide-spread general-purpose multi-body-system software ADAMS (Automatic Dynamic Analysis of Mechanical Systems), distributed by MSC.Software. ADAMS is applied and verified in many different industries such as aviation and car engineering. The capabilities of a multi-body-system to model elastic structures with any possible degree of freedom are more sophisticated than the limited list of model parameters within FAST and DHAT. For instance the ADAMS-models considered blade torsional elasticity in conjunction with coupling of edge and flap motion which is not possible in the current version of FAST. Since the standard version of ADAMS does not include an aerodynamic module, the NREL AeroDyn subroutine has been linked to ADAMS as well. Thus, both the NREL codes apply the same aerodynamic loads to the structural elements. NREL developed a pre-processor for generating wind turbine models for the ADAMS-input. Based on a FAST wind turbine model, the tool translates the FAST input data into an ADAMS compatible format.

The simulation codes applied for this evaluation project are listed in the following table:

Module	Version	Date
FAST	5.1	September 2004
ADAMS	2003	2003
AeroDyn (included in FAST and ADAMS)	12.57	29-09-2004
DHAT	19	September 2001

Table 1: Applied software codes for the load comparison

The principal data of the evaluated turbines are shown in Table 2 and Table 3. Further aerodynamic and structural data, as well as dimensions, are stated in the documentation.

UAE turbine model		
Rated electrical power	11	kW
Power control	stall	
Rotor diameter	10.0	m
Hub height	12.0	m
Rated rotor speed	72.0	rpm
Tilt angle	0.0	°
Cone angle (windward)	0.0	°
Blade mass	61.0	kg
Hub mass less blades	457.0	kg
Distance rotor to centre tower axis	1.4	m
Nacelle mass without hub and blades	1 255.0	kg

Nacelle mass centre without rotor (distance behind tower axis)	0.63	m
Gear ratio	25.13	-
Distance rotor plane to main bearing	0,33	m
Rated wind speed (10-min-mean-value)	9.0	m/s
Blade set angle (between rotor plane and 0°-chord line at 76% R)	4.815	°
Blade type	NREL twisted and tapered design	

Table 2: Principal data of test wind turbine UAE (all wind speed data related to hub height)

WindPact 1.5 model		
Rated electrical power	1 500	kW
Rotor diameter	70.0	m
Hub height	84.0	m
Variable rotor speed range	10.0 ... 20.0	rpm (±10%)
Rated rotor speed	20.0	rpm
Tilt angle	5.0	°
Cone angle (windward)	0.0	°
Blade mass	3 912	kg
Hub mass less blades	15 148	kg
Distance rotor to centre tower axis	3.3	m
Nacelle mass without hub and blades	51 170	kg
Nacelle mass centre without rotor (distance behind tower axis)	0.145	m
Gear ratio	87.97	-
Distance rotor plane to main bearing	0.99	m
Cut-in wind speed (10-min-mean-value)	4.0	m/s
Rated wind speed (10-min-mean-value)	12.0	m/s
Cut-out wind speed (10-min-mean-value)	25.0	m/s
Blade pitch adjustment range (full blade)	0.0°... +90.0°	
Blade type	WindPACT	

Table 3: Principal data of test wind turbine WindPACT 1.5 (all wind speed data related to hub height)

In order to ensure identical structural behavior the eigenfrequencies and Campbell diagrams of both test turbine models have been compared. In the calculations, the following eigenfrequencies have been used:

Components	UAE	WindPact 1.5
Blade flapwise 1. mode	6.93	1.23
Blade flapwise 2. mode	29.63	3.78
Blade edgewise 1. mode	8.71	1.71
Tower fore-after 1. mode	1.65	0.40
Tower side-side 1. mode	1.65	0.40
Tower fore-after 2. mode	12.85	-
Tower side-side 2. mode	13.57	-
Drive train torsional	2.46	18.41

Table 4: Eigenfrequencies in Hz of the two test turbines

The coordinate system applied in all calculations corresponds to the "Guideline for the Certification of Wind Turbines", edition 2003, of GL Wind. The coordinate system is provided in Annex A of this report.

4.2 Extreme loads

The applied load cases were defined to separate the different load groups and their contribution on the total load. The load cases operating in a vacuum (fixed rotor speed) eliminate any participation of aerodynamic loads. Additionally, all elastic properties were switched off. These cases delivered loads generated only by mechanical properties such as masses, static moments, and inertias. In a second step, the elasticity of blades, drive train and tower have been activated. Still operating in a vacuum, special turbine maneuvers have been simulated (constant rotor speed, constant yaw rate). These cases showed typical structural dynamics and the corresponding loads.

The next set of load cases include the full aerodynamic behavior. First, a constant-wind model and sinusoidal gust were introduced. This load case group is appropriate for investigating the behavior of the pitch and torque controller and the corresponding aerodynamic effects. Another variation of a constant wind model was the so called "abrupt wind drop". In this artificial load case a high wind speed of 60 m/s drops down to zero within one time step. The sudden release from aerodynamic loads lead to a strong excitation of the entire structure and delivered significant information about the damping properties.

The extreme design loads of all analyzed load cases are compiled in tables for the blade root, main bearing (fixed and rotating), tower top and tower bottom. Additionally, blade sectional loads were calculated in the edge and flapwise directions at the blade root and at 50% rotor radius.

As a result of the extreme load comparison, the deviations found between the codes are within technical tolerances. Higher deviations could be identified as a result of using different controller subroutines. Because of technical reasons, the controller code used for FAST and ADAMS was not compatible with DHAT subroutines. Some selected, representative plots of extreme load time series can be found in Annex C and Annex D.

4.3 Fatigue loads

The fatigue loads were simulated using a turbulent wind model including a three-dimensional, three -component anisotropic wind field and taking into account the structural dynamics of the turbine. The turbulence intensity corresponds to the GL Wind Guidelines, Edition 2003, Class II-A. A wind shear with a power law exponent of $\alpha = 0.2$ and without upflow angle was used. Only normal-operation conditions have been considered to reduce statistical scatter for the comparison (wind speed between cut-in and cut-out). The turbulent wind model and its parameters have not been assessed in detail. The applied turbulence intensities and mean wind speeds are assumed to be implemented in the turbine calculation codes correctly.

The load spectra were determined according to GL Wind Guidelines, Edition 2003, using a Rayleigh distribution of the wind speed with an annual mean wind speed of 8.5 m/s and a 20-year life time. The load cycles were counted using the Rainflow counting method. Unclosed cycles were counted as half cycles.

As a result, Rainflow counts, cumulative fatigue spectra, damage-equivalent loads and probability-mass functions have been compared. Additionally, a turbulent power curve and a Campbell diagram have been extracted from this simulation.

The first plausibility check, the comparison of the turbulent power curve, showed a very good agreement between FAST and DHAT results. The deviation to the ADAMS power curve of the WindPACT1.5 turbine is assumed to be caused by controller differences. Probably, the blade torsional degree of freedom available only in ADAMS has a significant influence too. Although different turbulent wind generators have been used for FAST and ADAMS on one side and DHAT on the other, the load levels and amplitude ranges found were in good accordance. Consequently, the cumulative spectra agreed as well.

Some selected turbulent time series are presented in Annex E. The power curves extracted from turbulent wind simulation are shown in Annex F. Examples of the cumulative fatigue spectra of the WinPACT1.5 blade root are shown in Annex G.

5 Conclusion

Load calculations under selected environmental conditions have been carried out using the design codes FAST, developed by NREL, and MSC.Software's ADAMS (both including NREL's AeroDyn module), and were compared to GL's in-house DHAT simulation code. All involved codes used the same turbine properties. The comparison revealed the pro's & con's of each individual code. FAST, ADAMS and DHAT use the same approach for calculating aerodynamic forces. As expected, the aerodynamic output was found very similar. However, the existing differences in some aerodynamic features (e.g. the stall hysteresis model) did not drive the final load results. Some deviations found have been localized resulting from different approaches for calculating dynamic responses from flexible structures. Especially for the rotor blade, the multi-body-system approach of ADAMS, including a higher number of degrees of freedoms, showed higher structural responses.

The applied tools for pre-processing the FAST and ADAMS input data and analyzing the time domain output have not been assessed within this study.

For both test turbines, the loads calculated with FAST and ADAMS showed good agreement with GL Wind's parallel calculation. The two evaluated codes, FAST and ADAMS, are considered to be suitable tools for determining loads of current wind turbine designs. The calculated data can be used for a wind turbine certification procedure.

6 Annexes

Attached to this report are extracts from the documents as follows:

A Co-ordinate systems (2 pages)

B Analysed turbine sections and simulation parameters (1 page)

C Example time series UAE turbine(1 page)

D Example time series WindPACT 1.5 (2 pages)

E Example time series - power production in turbulent wind (1 page)

F Turbulent power curves UAE and WindPACT 1.5 turbines (1 page)

G Example fatigue results – cumulative spectra blade root (1 page)

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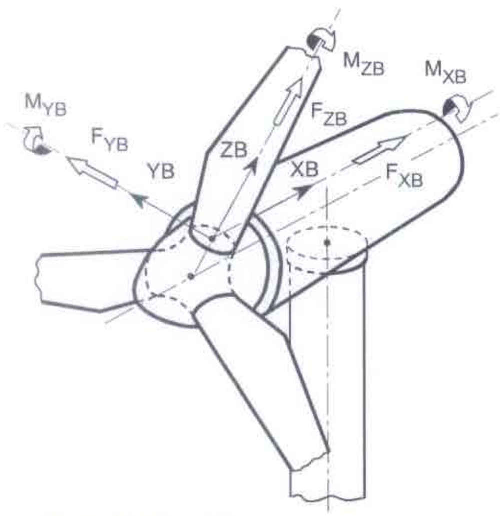
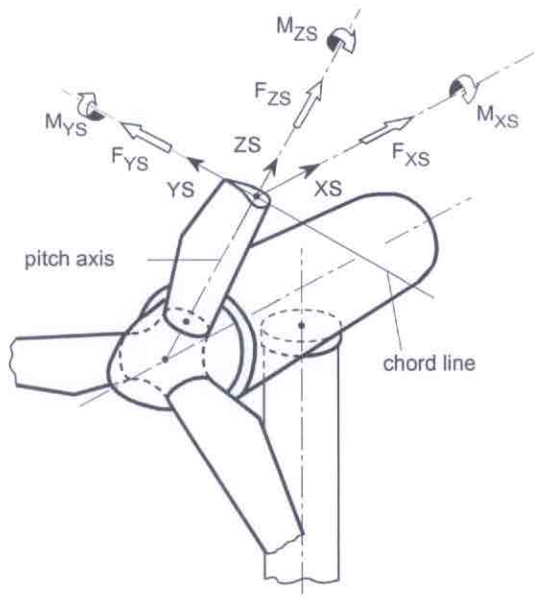
Annex A: GL Co-ordinate system



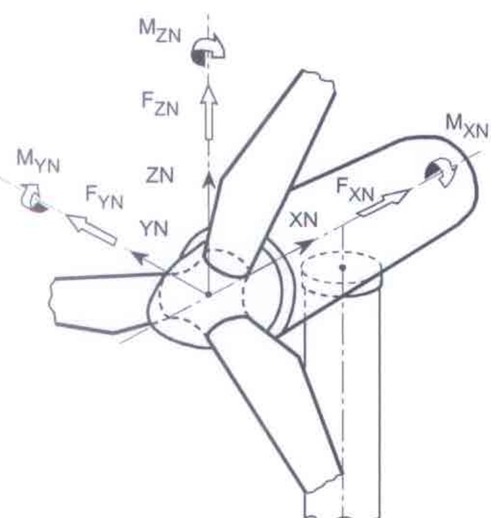
XB in direction of the rotor axis
ZB radially
YB so that XB, YB, ZB rotate clockwise

Fig. 4.A.1 Blade coordinate system



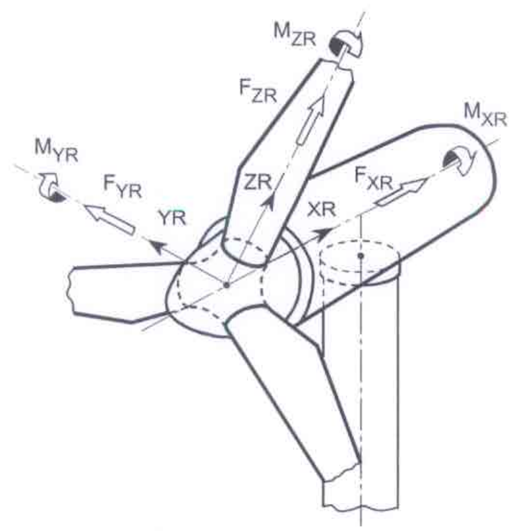
YS in direction of the chord, orientated to blade trailing edge
ZS in direction of the blade pitch axis
XS perpendicular to the chord, so that XS, YS, ZS rotate clockwise

Fig. 4.A.2 Chord coordinate system



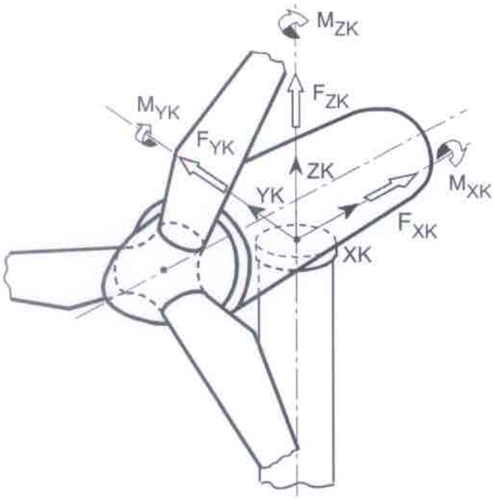
XN in direction of the rotor axis
ZN upwards perpendicular to XN
YN horizontally sideways, so that XN, YN, ZN rotate clockwise

Fig. 4.A.3 Hub coordinate system

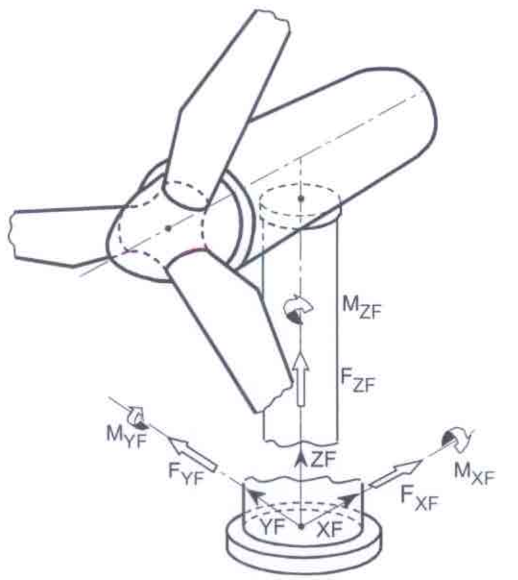


XR in direction of the rotor axis
ZR radially, orientated to rotor blade 1 and perpendicular to XR
YR perpendicular to XR, so that XR, YR, ZR rotate clockwise

Fig. 4.A.4 Rotor coordinate system



XK horizontal in direction of the rotor axis, fixed to the tower
ZK vertically upwards
YK horizontally sideways, so that XK, YK,ZK rotate clockwise



XF horizontal
ZF vertically upwards in direction of the tower axis
YF horizontally sideways, so that XF, YF, ZF rotate clockwise

Fig. 4.A.5 Tower top coordinate system

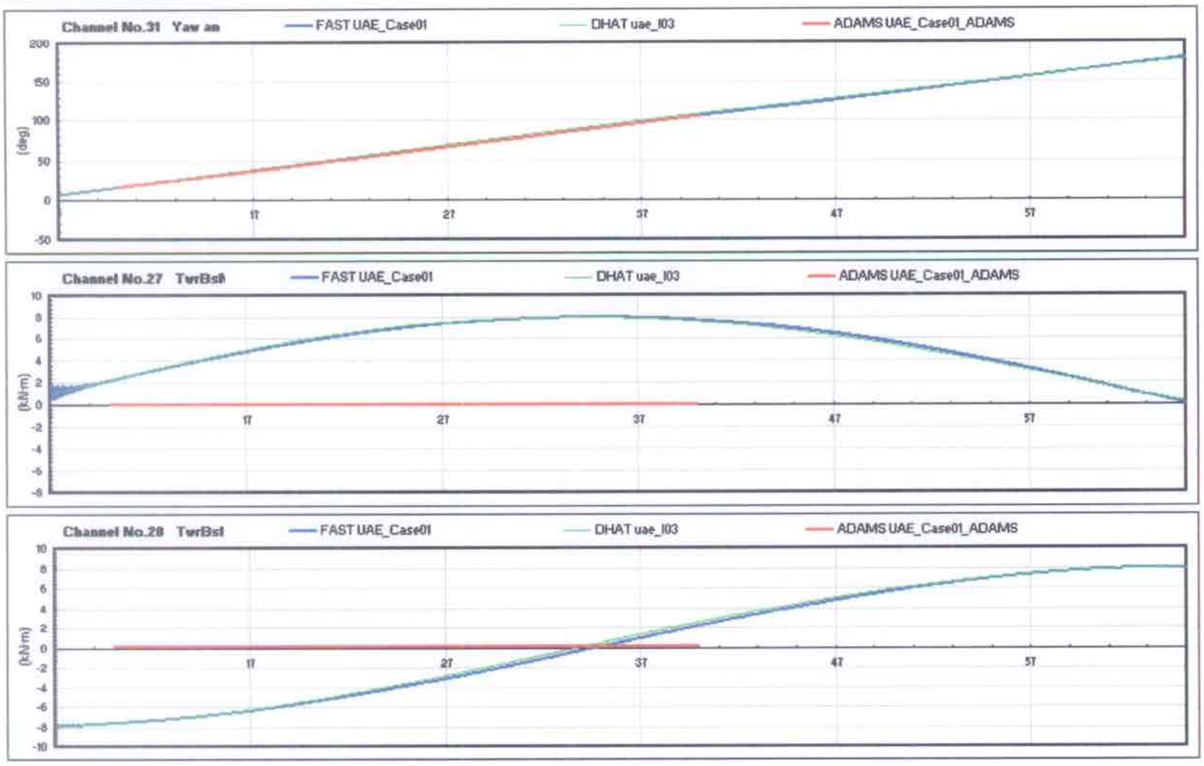
Fig. 4.A.6 Tower bottom coordinate system

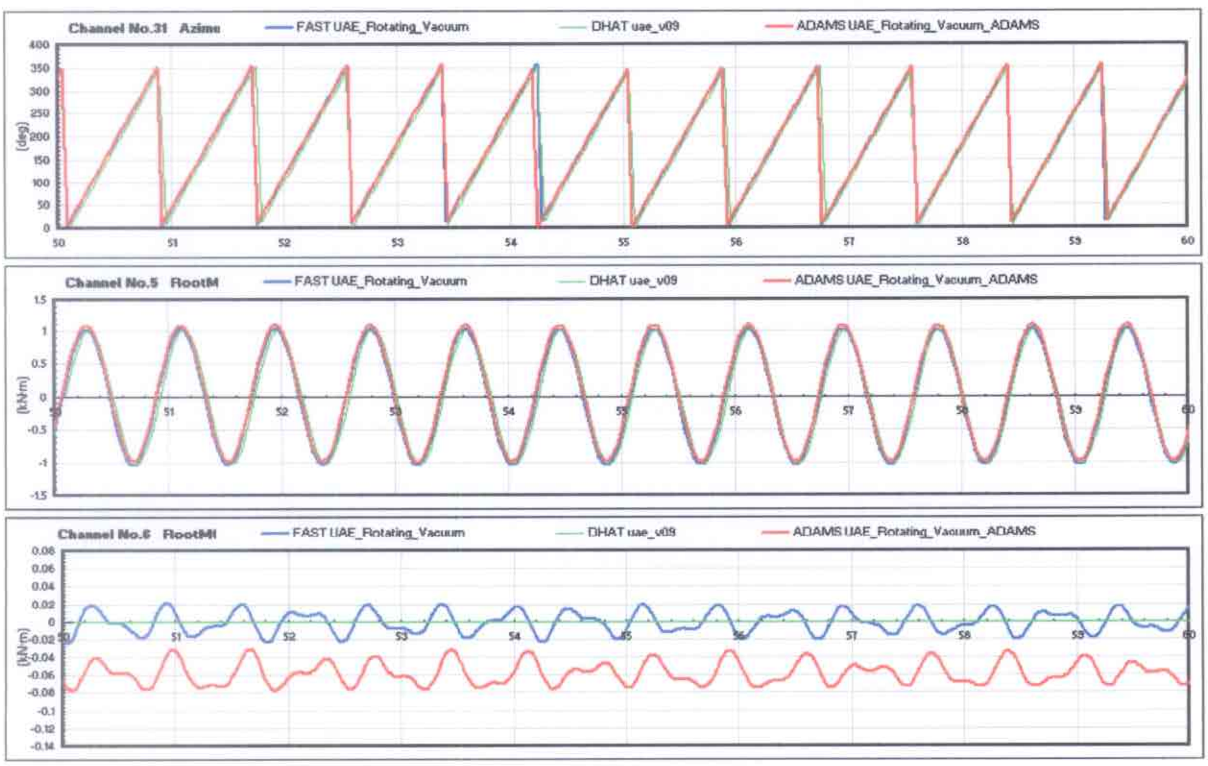
Annex B: Analysed turbine sections and simulation parameters

Loads		No.	GL-System	DHAT-Channel	FAST / ADAMS Channel
Blade	Edge / flap at about 0.5 R	1	MxS1(8)	101	Spn8MLxb1
		2	MyS1(8)	102	Spn8MLyb1
	Edge / flap at blade root #1	3	MxS1(1)	48	RootMEdg1
		4	MyS1(1)	49	RootMFlp1
	Root #1	5	MxB1	54	RootMIP1
		6	MyB1	55	RootMOoP1
		7	MzB1	56	RootMzc1
		8	FxB1	51	RootFxc1
		9	FyB1	52	RootFyc1
		10	FzB1	53	RootFzc1
	Root #2	11	MxB2	57	RootMIP2
		12	MyB2	58	RootMOoP2
	Root #3 (optional for 3 blades)	13	(MxB3)	59	(RootMIP3)
		14	(MyB3)	60	(RootMOoP3)
Hub/shaft	Non-rotating	15	MxN	70	RotTorq
		16	MyN	71	LSSGagMys
		17	MzN	72	LSSGagMzs
		18	FxN	67	RotThrust
		19	FyN	68	LSSGagFys
		20	FzN	69	LSSGagFzs
	Rotating	21	MyR	77	LSSGagMya
		22	MzR	78	LSSGagMza
Tower	Yaw bearing (rot. with nac.)	23	MxK	85	YawBrMxn
		24	MyK	86	YawBrMyn
		25	MzK	84	YawBrMzn
		26	FxK	79	YawBrFxn
		27	FyK	80	YawBrFyn
		28	FzK	81	YawBrFzn
	Base	29	MxF	91	TwrBsMxt
		30	MyF	92	TwrBsMyt
Operating conditions		31	Long. Wind velocity	1	HorWindV
		32	Wind direction	4	HorWndDir
		33	Rotor position	6	Azimuth
		34	Rotational speed	7	RotSpeed
		35	Mechanical power	12	RotPwr
		36	Pitch (actuator set)	13	BldPitch1
		37	Brake moment at HSS	21	HSSBrTq
	Tip deflection	38	Tip defl. blade #1	23	OoPDefl1
		39	Tip defl. blade #2	24	OoPDefl2
	(optional for 3 blades)	40	(Tip defl. blade #3)	25	(OoPDefl3)

Annex C: Example time series UAE turbine

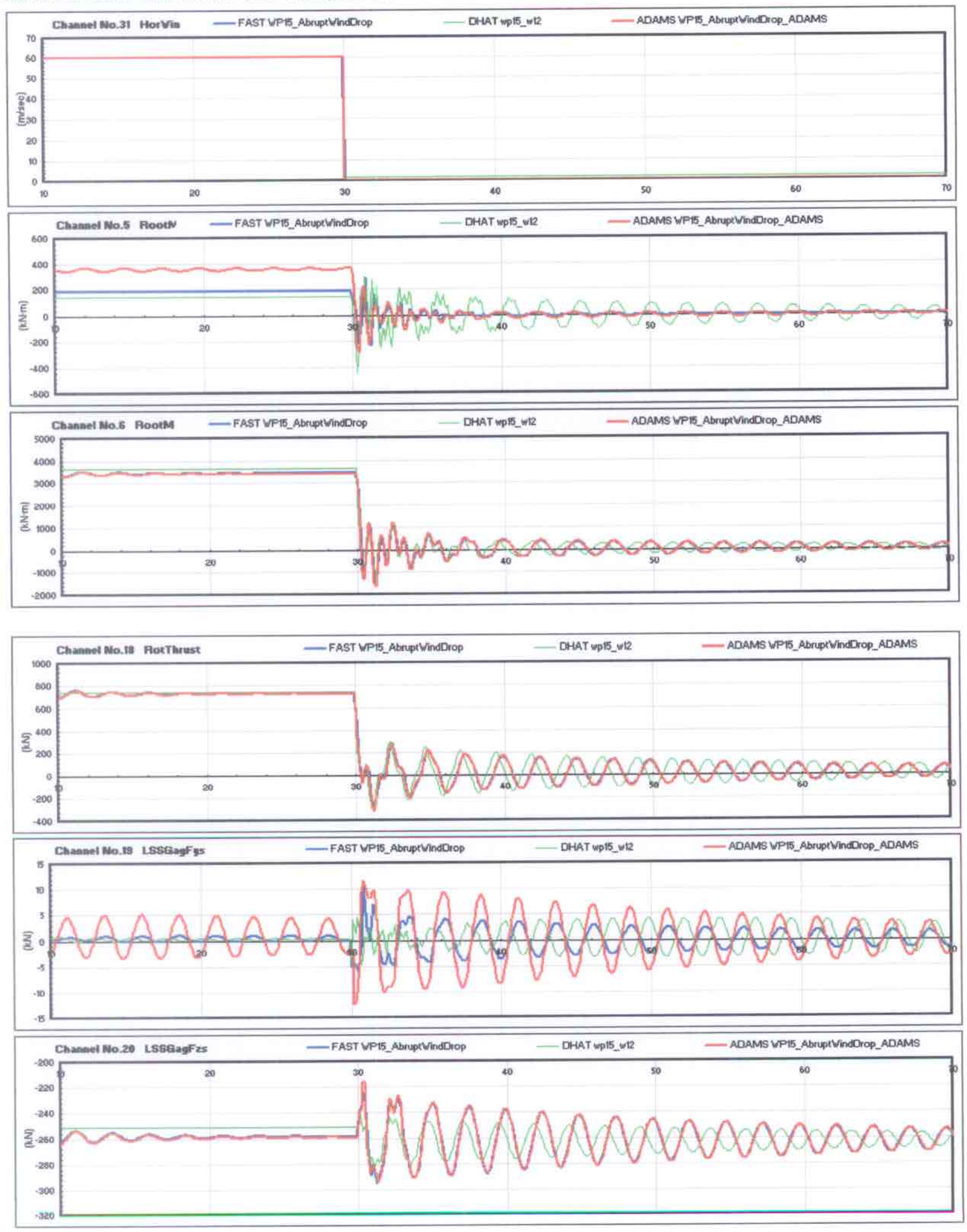
UAE Phase VI (upwind) with no DOFs in a vacuum : Bottom Moment





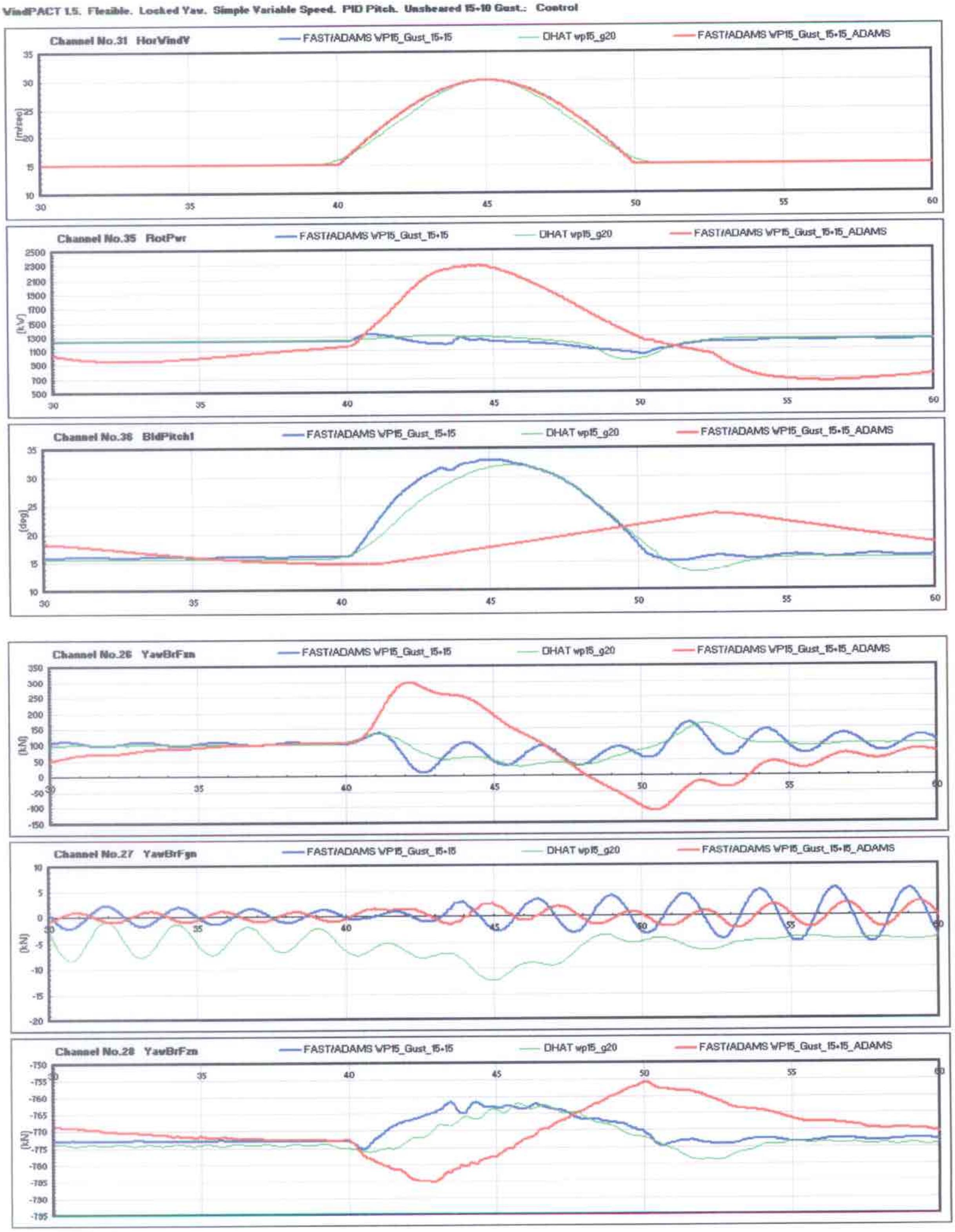
Annex D: Example time series WindPACT 1.5

WindPACT 1.5. Flexible. Generator locked. Pitch = 0. Abrupt wind drop: Root Moment



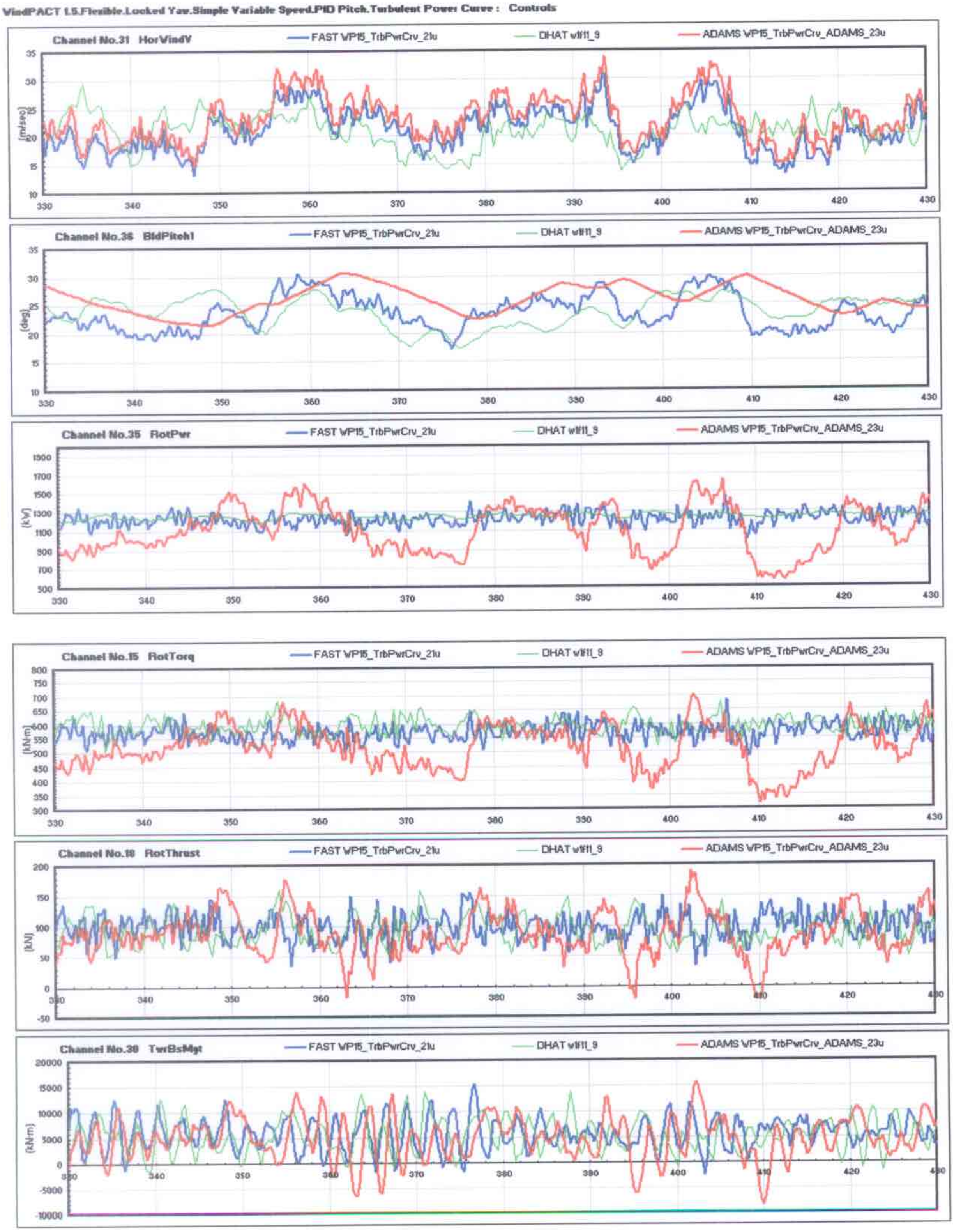
Annex D: Example time series WindPACT 1.5

WindPACT 1.5. Flexible. Locked Yaw. Simple Variable Speed. PID Pitch. Unsheared 15-10 Gust.: Control

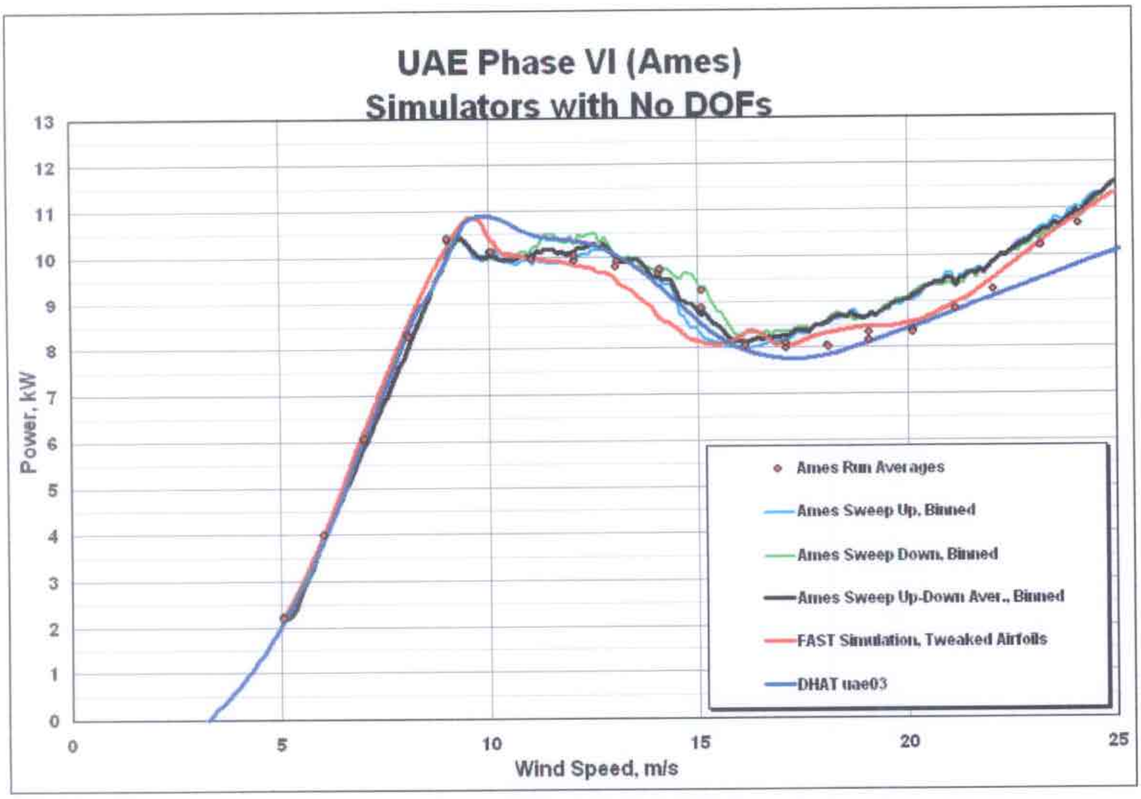


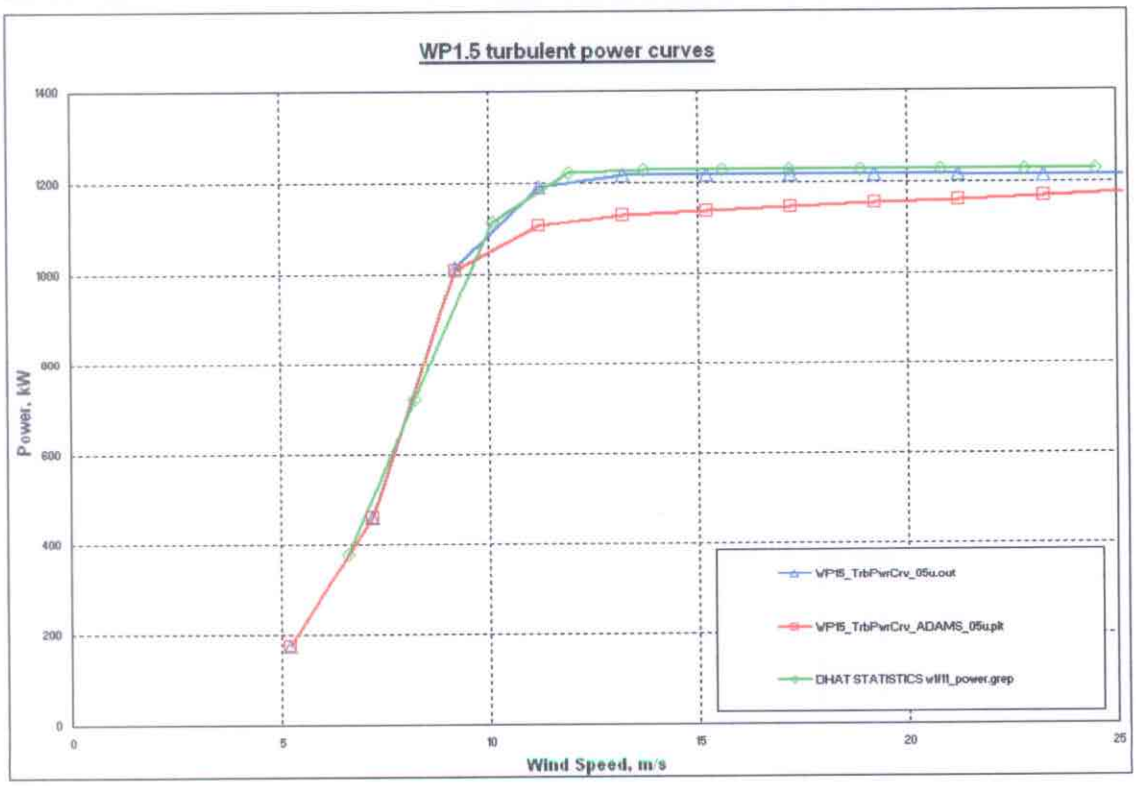
Annex E: Example time series - power production in turbulent wind

WindPACT 1.5.Flexible.Locked Yaw.Simple Variable Speed.PID Pitch.Turbulent Power Curve : Controls



Annex F: Turbulent power curves UAE and WindPACT 1.5





Annex G: Example fatigue results – cumulative spectra blade root