Design of Wind Energy Systems

CARL VON OSSIETZKY universität OLDENBURG

ForWind Center for Wind Energy Research

CIP Tutorial 6b
Hints for the calculation of extreme loads

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ForWind – Wind Energy Systems

Topics

- Extreme loads
- Load analysis – FAST
- Summary

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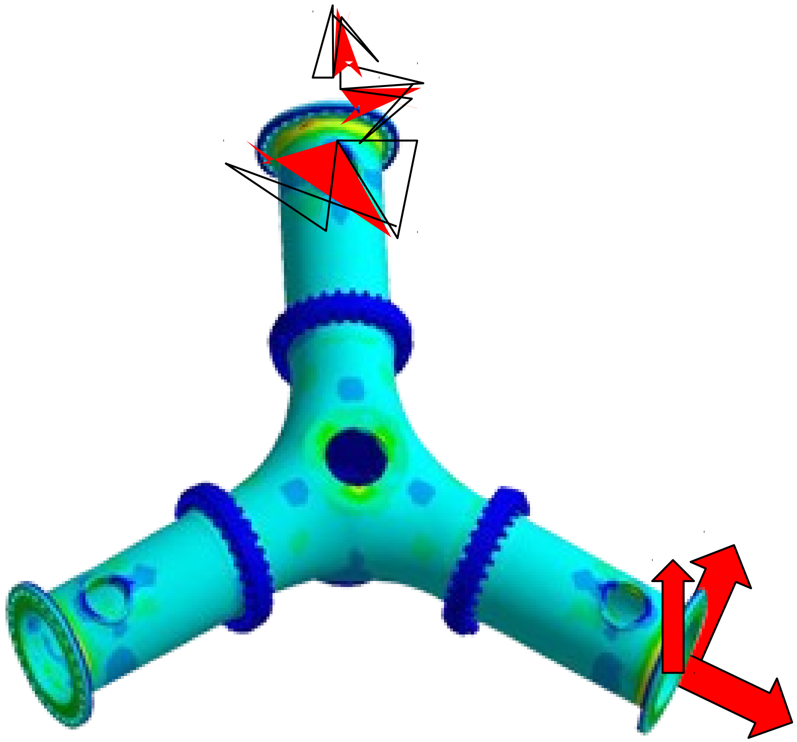
Extreme damage vs. fatigue damage

- Extreme damage leads to exceedance of strength durability
- Extreme loads lead in this case to the failure of a component or the whole structure
- Extreme loads table used for detailed component tests

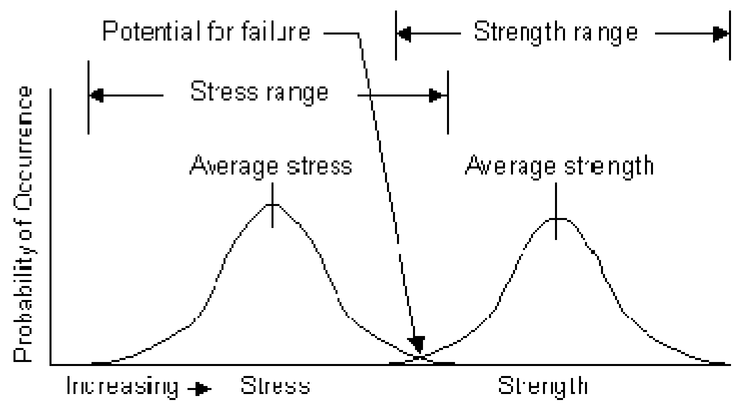


[calibertech.net]

Extreme load – safety factors

- Safety factor / design principles:
  - Fail-safe: component may fail without failure of the whole system (safe operation or can be brought to safe state in case of a failure)
  - Safe-life: Component will not fail until replaced after defined time
  - Damage-tolerant: component can sustain defects until repair is possible

- Safety factor defined for both material and load side, depending on design principle



- Safety factor here: 1

Extreme load cases – combinations

		External conditions		
		Normal	Extreme	Other
Operational conditions	Normal operation	Production (1.2), Park (6.4), Start (3.1), Stop (4.1), Emergency stop (5.1)	Production (1.1, 1.3,1.5) Park (6.1-6.3), Start (3.2, 3.3), Stop (4.2)	
	Failure	Production (2.1, 2.2, 2.4)	Production (2.3), Park and fault (7.1)	
	Transport, assembly, maintenance			Designer selection (8.1)

Load cases (IEC 61400-1)

DLC (design load cases) are formed by:

- Turbine operation status
  - Production, fault, start, stop, etc.
- Wind conditions
  - Normal, extreme (1-y,50-y return)
  - Turbulence, shear, direction
- Other conditions
  - Grid, control failure
- Type of analysis
  - Fatigue, extreme

Design situation	DLC	Wind condition		Other conditions	Type of analysis	Partial safety factors
1) Power production	1.1	NTM	$V_{in} < V_{hub} < V_{out}$	For extrapolation of extreme events	U	N
	1.2	NTM	$V_{in} < V_{hub} < V_{out}$		F	*
	1.3	ETM	$V_{in} < V_{hub} < V_{out}$		U	N
	1.4	ECD	$V_{hub} = V_r$-2m/s, V_r, V_r+2m/s		U	N
	1.5	EWS	$V_{in} < V_{hub} < V_{out}$		U	N
2) Power production plus occurrence of fault	2.1	NTM	$V_{in} < V_{hub} < V_{out}$	Control system fault or loss of electrical network	U	N
	2.2	NTM	$V_{in} < V_{hub} < V_{out}$	Protection system or preceding internal electrical fault	U	A
	2.3	EOG	$V_{hub} = V_r \pm 2m/s$ and V_{out}	External or internal electrical fault including loss of electrical network	U	A
	2.4	NTM	$V_{in} < V_{hub} < V_{out}$	Control, protection, or electrical system faults including loss of electrical network	F	*
3) Start up	3.1	NWP	$V_{in} < V_{hub} < V_{out}$		F	*
	3.2	EOG	$V_{hub} = V_{in}$, $V_r \pm 2m/s$ and V_{out}		U	N
	3.3	EDC	$V_{hub} = V_{in}$, $V_r \pm 2m/s$ and V_{out}		U	N
4) Normal shut down	4.1	NWP	$V_{in} < V_{hub} < V_{out}$		F	*
	4.2	EOG	$V_{hub} = V_r \pm 2m/s$ and V_{out}		U	N
5) Emergency shut down	5.1	NTM	$V_{hub} = V_r \pm 2m/s$ and V_{out}		U	N
6) Parked (standing still or idling)	6.1	EWM	*50 year recur. Period*		U	N
	6.2	EWM	*50 year recur. Period.*	Loss of electrical network connection	U	A
	6.3	EWM	1 *year recur. Period*	Extreme yaw misalignment	U	N
	6.4	NTM	$V_{hub} < 0.7\ V_{ref}$		F	*
7) Parked and fault conditions	7.1	EWM	1 *year recur. period*		U	A
8) Transport, assembly, maintenance and repair	8.1	NTM	*V_{maint} to be stated by the manufacturer*		U	T
	8.2	EWM	1 *year recur. period*		U	A

Extreme load cases – in CIP tutorial

Design situation	DLC	Wind condition	Wind speed	Other conditions	Type of analysis	Partial safety factors
Power production	1.5	EWS	Vin<Vhub<Vout		U	N
Power production & fault	2.3	EOG	Vr±2 m/s & Vout	External or internal electrical fault including loss of electrical network	U	A

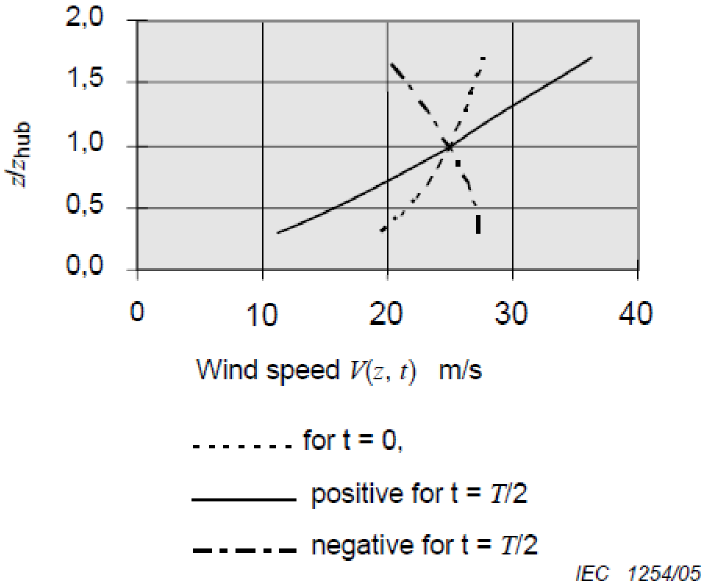
Extreme load – power production

- DLC 1.5 – Load case requirements:

  I. *“In this design situation, a wind turbine is running and connected to the electric load...”*

  II. “… and DLC 1.5 specify transient cases that have been selected as potentially critical events in the life of a wind turbine.”

  III. Examples of extreme vertical wind shear:



Extreme load – power production & fault

- DLC 2.3 - Load case requirements:

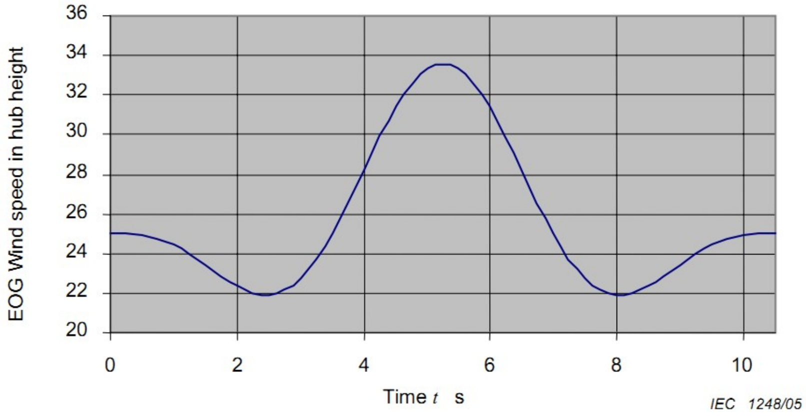
  I. *“This design situation involves a transient event triggered by a fault or the loss of electrical network connection while the turbine is producing power“*

  II. *“For DLC 2.3 the potentially significant wind event, EOG, is combined with an internal or external electrical system fault (including loss of electrical network connection) and considered as an abnormal event”*

  - *We will stop the machine, and thus assume no significant fatigue damage*

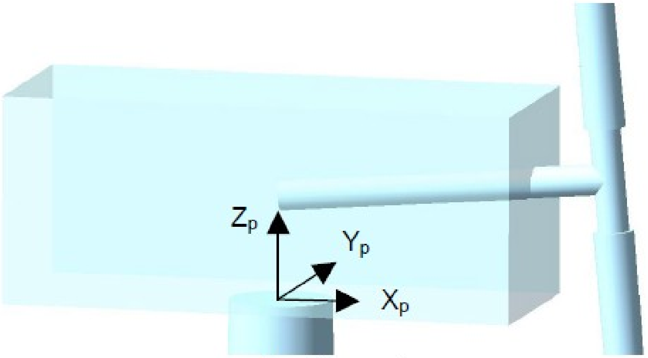
EOG – 1 year return period

EOG – 50 year return period



Extreme load case table

- Example of extreme load case table for tower top loads analysis



coordinate system.

FAST manual

K_2-System (tower top, fixed yaw system), incl. Load safety factors

	Load case	F_x	F_y	F_z	M_x	M_y	M_z	F_r	M_r	TimeSer	s_{f_load}
		[kN]	[kN]	[kN]	[kNm]	[kNm]	[kNm]	[kN]	[kNm]		
Min	1.5	-496.92	-24.76	-1174.90	-13.34	-1651.40	-678.42			15_vr_y00_c_00	1.35
Max	1.5	491.70	-12.84	-1207.90	1714.90	104.09	-137.95			15_vr_Yp8_d_30	1.35
Min	6.1	26.16	-471.53	-1166.00	701.73	-645.26	1460.50			61_m08_05	1.35
Max	6.1	9.19	493.39	-1117.80	-604.94	-450.69	-296.17			61_p08_04	1.35
Min	8.1	12.87	22.39	-1387.30	815.93	-1146.80	90.84			81_646_120	1.50
Max	7.1	32.25	23.57	-789.70	-103.77	-52.62	-995.97			71m8_605_03	1.10
FRMax	1.5	-496.92	-24.76	-1174.90	-13.34	-1651.40	-678.42	**497.5**		15_vr_y00_c_00	1.35
Min	8.1	-25.71	-19.17	-1340.70	-1582.00	-1155.60	220.13			81_627	1.50
Max	8.2	14.18	-31.02	-936.36	2292.40	-832.08	66.76			82_5	1.10
Min	1.3	-118.83	74.05	-1195.20	400.06	-4645.80	-567.36			13_vr_dp_60_p8	1.35
Max	2.2	-52.20	-39.47	-935.38	75.13	3013.50	182.09			22_vr_m8_120	1.10
Min	2.2	-152.39	14.57	-943.79	-338.85	-561.57	-3825.00			22_vr_00_30	1.10
Max	2.2	69.87	-87.39	-986.14	456.04	-532.34	3893.80			22_vr_p8_210	1.10
MRMax	1.3	-118.83	74.05	-1195.20	400.06	-4645.80	-567.36		**4662.99**	13_vr_dp_60_p8	1.35

Example table

Extreme loads – CIP tutorial

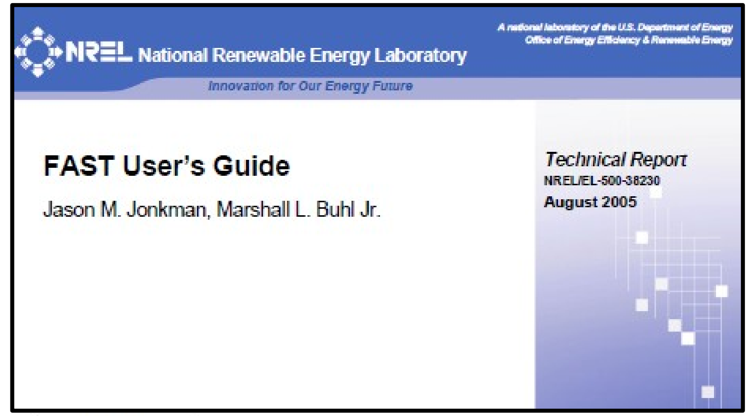
- Example of extreme load case table in DoWES class
- Include:
  - Min / Max values
  - Forces / Moments
  - Load cases

Note: coordinate systems can be found in FAST users guide

Sensor	Unit	Min/Max	DLC x	DLC x	DLC x
RootMxc2	kNm	Min Max			
RootMyc2	kNm	Min Max			
RootMzc2	kNm	Min Max			
RootFxc2	kN	Min Max			
RootFxy2	kN	Min Max			
RootFxz2	kN	Min Max			
TwrBsMxt	kNm	Min Max			
TwrBsMyt	kNm	Min Max			
TwrBsMzt	kNm	Min Max			
TwrBsFxt	kNm	Min Max			
TwrBsFyt	kNm	Min Max			
TwrBsFzt	kN	Min Max			

Load analysis – FAST

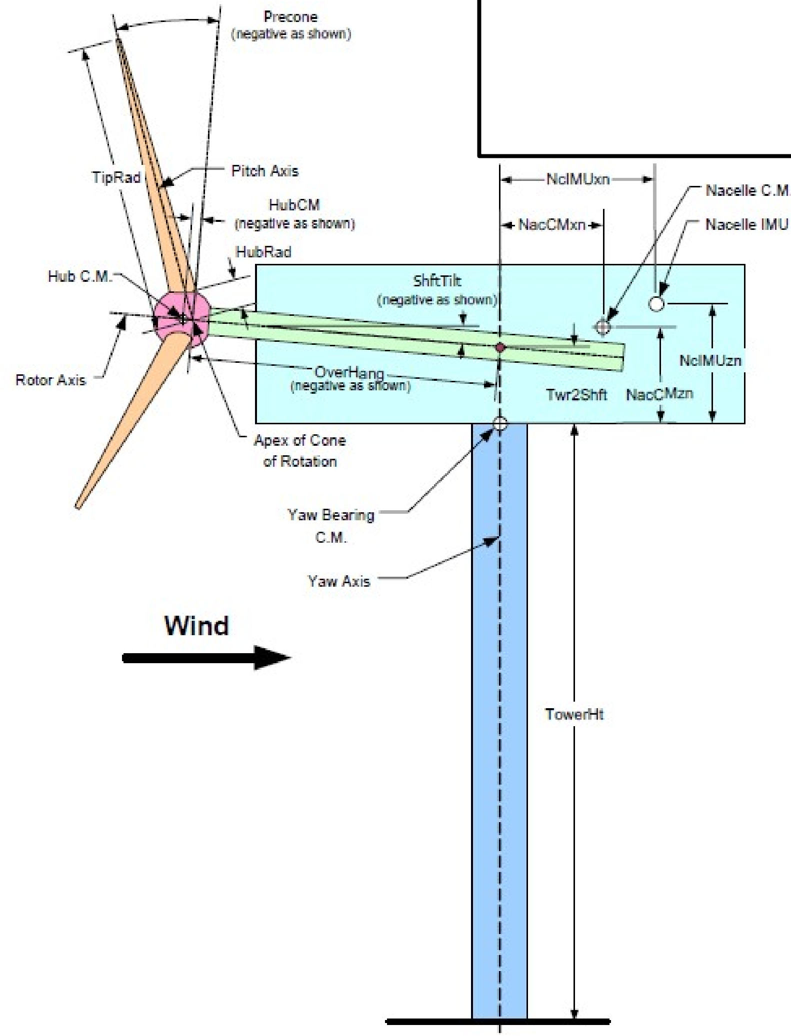
- Overview
- Test case
- *Load calculation*


NREL National Renewable Energy Laboratory
Innovation for Our Energy Future
A national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy

FAST User's Guide

Jason M. Jonkman, Marshall L. Buhl Jr.

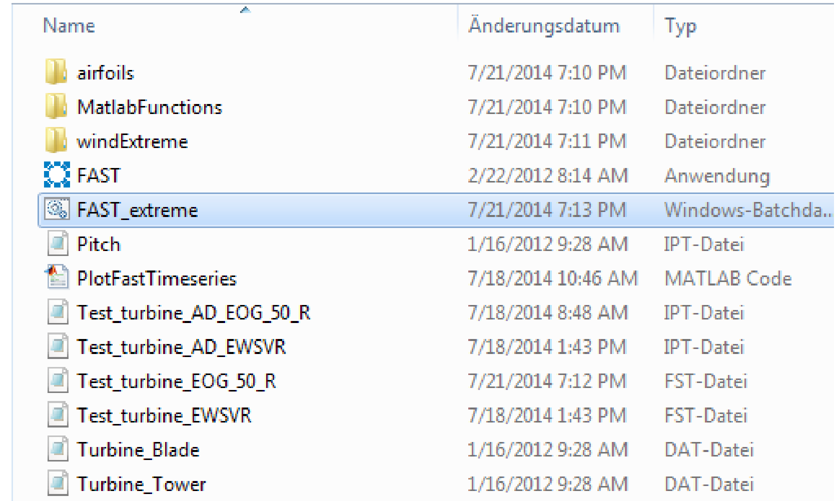
Technical Report
NREL/EL-500-38230
August 2005



Test case – FAST (1/5)

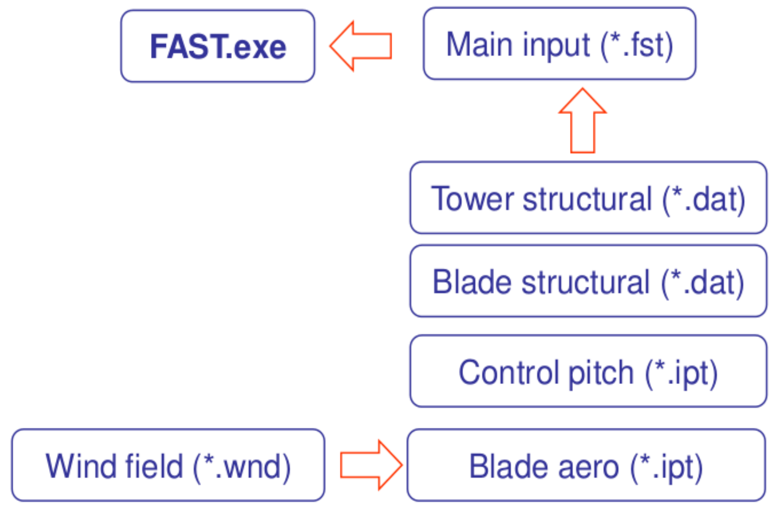
1. Unpack zip folder as C:\ FASTextreme
2. Explore folder; it contains:
   - FAST.exe - executable
   - *.fst – main input file & reference to other input files
   - *_blade.dat & *_tower.dat, Pitch.ipt – other input files
   - *_AD.ipt – Aerodynamics & reference to wind file
   - Folders with airfoils & wind files
   - Matlab script & folder with functions

2



Name	Änderungsdatum	Typ
airfoils	7/21/2014 7:10 PM	Dateiordner
MatlabFunctions	7/21/2014 7:10 PM	Dateiordner
windExtreme	7/21/2014 7:11 PM	Dateiordner
FAST	2/22/2012 8:14 AM	Anwendung
FAST_extreme	7/21/2014 7:13 PM	Windows-Batchda...
Pitch	1/16/2012 9:28 AM	IPT-Datei
PlotFastTimeseries	7/18/2014 10:46 AM	MATLAB Code
Test_turbine_AD_EOG_50_R	7/18/2014 8:48 AM	IPT-Datei
Test_turbine_AD_EWSVR	7/18/2014 1:43 PM	IPT-Datei
Test_turbine_EOG_50_R	7/21/2014 7:12 PM	FST-Datei
Test_turbine_EWSVR	7/18/2014 1:43 PM	FST-Datei
Turbine_Blade	1/16/2012 9:28 AM	DAT-Datei
Turbine_Tower	1/16/2012 9:28 AM	DAT-Datei

FAST folder

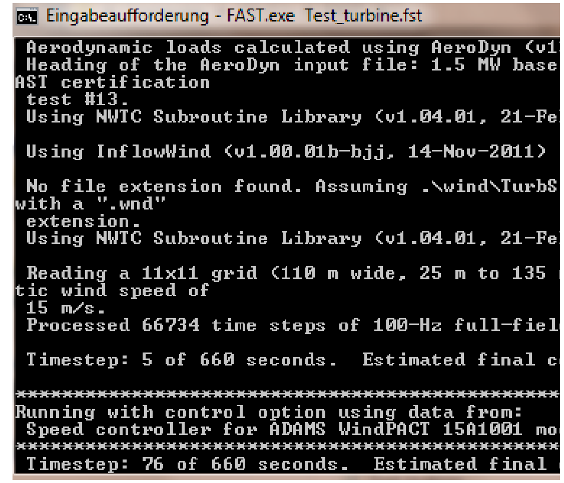


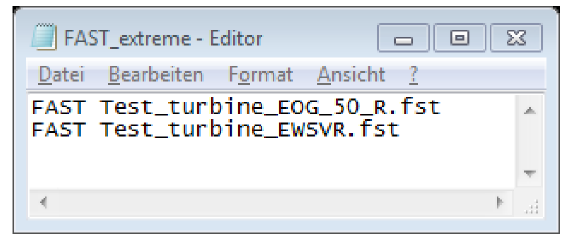
Test case – FAST (2/5)

3. In DOS prompt go to directory where FAST has been installed (see 1)

   a) Run input files one by one or…

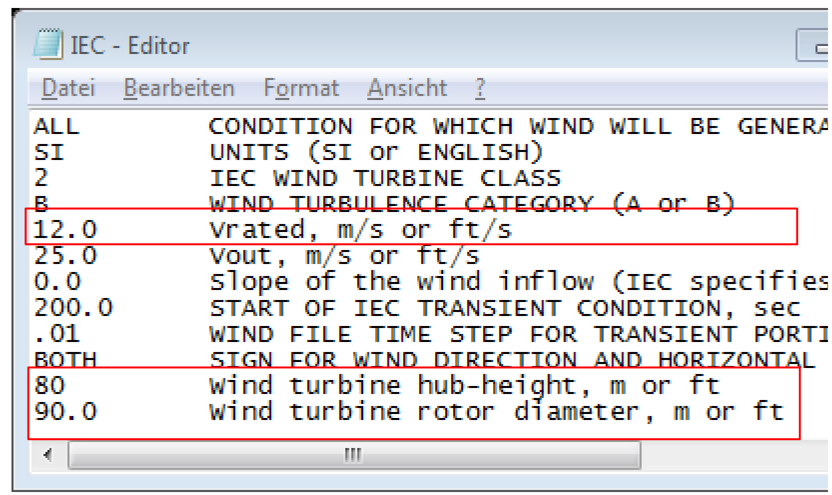
   b) Run input files in a batch mode, for example: **FAST_extreme.bat**





NOTE: for your own turbine, update wind files (\windExtreme\IEC.ipt) and run IECwind

- FAST, AeroDyn and IECwind user manuals
- Specific instructions in Stud.IP
- Windfiles: **\windExtreme\IECwind.exe**



Test case – FAST (3/5)

4. Review results in folder:
   - Test_*.opt – AeroDyn echo
   - Test_*.fsm – FAST summary
   - Test_*.out – FAST output file
5. Review results in Test_*.out file:
   - Results in columns: first one is time, followed by wind speed and all other outputs, at the bottom of input file Test_*.fst

4

Test_turbine	FST-Datei
Test_turbine	OPT-Datei
Test_turbine	FSM-Datei
Test_turbine	OUT-Datei

FAST output files in folder

5

```
These predictions were generated by FAST (v7.01.00a-bjj, 16-Fe
The aerodynamic calculations were made by AeroDyn (v13.00.01a-

 Test file with data from WindPACT 1.5 MW turbine. LVT July 20

Time     WindVxi  WindVyi  WindVzi  RootMFlp2          RootMedg2
(s)      (m/s)    (m/s)    (m/s)    (kN·m)   (kN·m)    (kN)     (rpm)
  60.000           1.571E+01          5.766E-01          3.609E-01
  60.050           1.586E+01          1.097E-01          1.980E-01
  60.100           1.584E+01          1.285E-01          1.909E-01
  60.150           1.558E+01          5.162E-01          1.924E-01
  60.200           1.544E+01          6.082E-01         -2.012E-01
  60.250           1.513E+01          6.655E-01          1.477E-01
  60.300           1.482E+01          3.873E-01          3.654E-02
  60.350           1.543E+01          2.545E-01          4.254E-01
  60.400           1.550E+01          1.946E-02         -1.820E-01
  60.450           1.567E+01          1.844E-01          2.154E-01
  60.500           1.572E+01          3.871E-02         -4.945E-02
  60.550           1.614E+01          3.273E-01          3.548E-01
  60.600           1.641E+01          2.911E-01          7.701E-02
  60.650           1.627E+01         -4.224E-02          3.447E-01
  60.700           1.662E+01          6.203E-02          2.634E-01
  60.750           1.612E+01          5.939E-02          1.042E-02
  60.800           1.611E+01          4.565E-02          9.533E-01
  60.850           1.573E+01          3.007E-01          5.154E-01
  60.900           1.548E+01          1.501E-01          3.261E-01
  60.950           1.528E+01          5.610E-01          5.200E-01
  61.000           1.548E+01          8.214E-01          3.865E-01
  61.050           1.554E+01          7.147E-01          3.060E-01
  61.100           1.545E+01          1.105E+00          1.316E+00
  61.150           1.583E+01          2.144E+00          8.971E-01
  61.200           1.581E+01          2.681E+00          4.444E-01
  61.250           1.540E+01          2.230E+00          1.125E+00
  61.300           1.584E+01          2.244E+00          9.916E-01
  61.350           1.599E+01          1.859E+00          1.924E+00
  61.400           1.625E+01          1.966E+00          1.553E+00
  61.450           1.621E+01          1.948E+00          1.900E+00
  61.500           1.597E+01          2.033E+00          1.739E+00
```

FAST main output file

Test case – FAST (4/5)

6. Analyse results (timeseries) using Matlab script in folder:
   - PlotFastTimeseries.m
7. Timeseries statistics (a) & damage equivalent loads (b) can be read directly from Matlab workspace

6

airfoils	Dateiordner
wind	Dateiordner
MatlabFunctions	Dateiordner
Pitch	IPT-Datei
Turbine_Blade	DAT-Datei
Turbine_Tower	DAT-Datei
Disclaimer	Textdokument
FAST	Anwendung
Test_turbine_AD	IPT-Datei
PlotFastTimeseries	MATLAB Code
Test_turbine	FST-Datei

7a

Workspace

Name	Value
Damage_Eq_Loads	<1x1 struct>
FAST_output_file_...	'C:\FAST\Test_
FAST_results	<1x1 struct>

FAST_results ×

FAST_results <1x1 struct>

Field	Value	Min	Max	Mean	Std
header	<1x13 cell>				
Time	<12001x1 double>	60	660	360	173.2267
WindVxi	<12001x1 double>	9.0490	21.8600	14.9613	1.9743
WindVyi	<12001x1 double>	-5.1720	4.4750	-0.0479	1.3500
WindVzi	<12001x1 double>	-3.5220	2.8440	-0.0060	0.8048
RootMFlp2	<12001x1 double>	31.5700	1482	802.9375	215.2980
RootMedg2	<12001x1 double>	-497.3000	572.4000	26.5339	316.1732
RotThrust	<12001x1 double>	97.3200	212.2000	151.6548	18.5404
RotSpeed	<12001x1 double>	19.4800	21.4500	20.4751	0.3443
TwrBsMyt	<12001x1 double>	4814	15330	9.9923e+03	1.6872e+03
TwrBsMxt	<12001x1 double>	-1110	2728	801.4473	543.3289
GenPwr	<12001x1 double>	1294	1572	1.4818e+03	49.8799
GenTq	<12001x1 double>	7.5900	8.3770	8.2679	0.1528
BldPitch2	<12001x1 double>	7.4160	20.5700	14.1270	2.7531

7b

Workspace

Name	Value
Damage_Eq_Loads	<1x1 struct>
FAST_output_file_...	'C:\FAST\Test_
FAST_results	<1x1 struct>

Damage_Eq_Loads <1x1 struct>

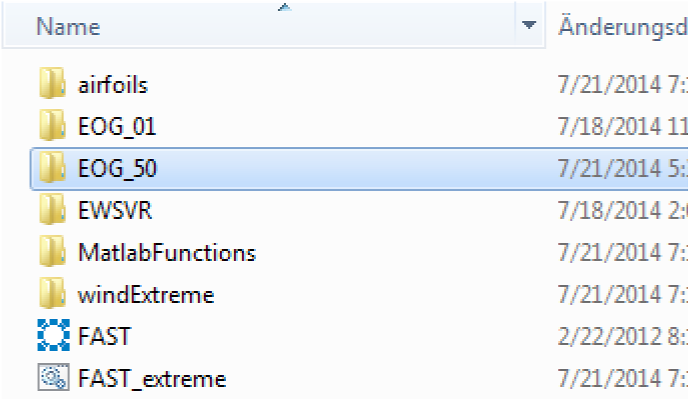
Field	Value
RootMFlp_Req	606.9395
RootMFlp_m	10
RootMedg_Req	790.7247
RootMedg_m	10
TwrBsMyt_Req	2.0539e+03
TwrBsMyt_m	4
TwrBsMxt_Req	1.1630e+03
TwrBsMxt_m	4

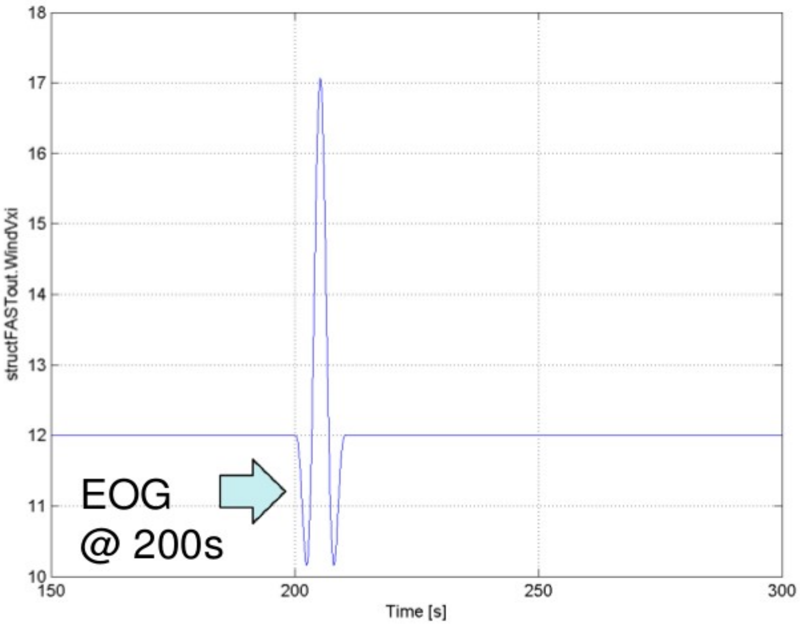
Test case – FAST (5/5)

Rated power

8

8. Rename folders simplify track of outputs (example with: EOG_50)
9. Description of outputs in Turbine_*.fst

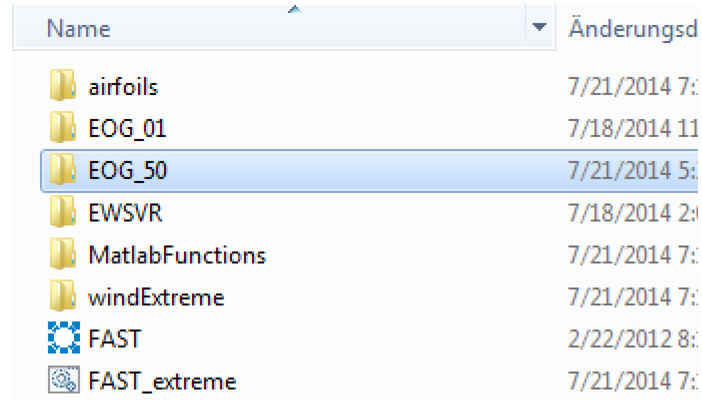




Test case – FAST (5/5)

Rated power

8



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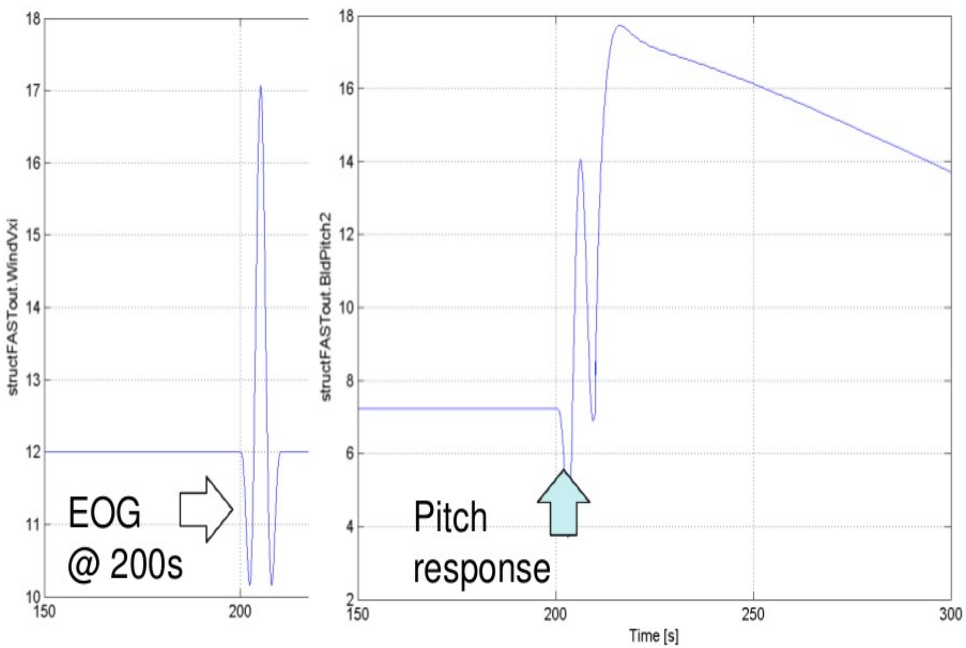

Test case – FAST (5/5)

Rated power

8

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   (example with: EOG_50)

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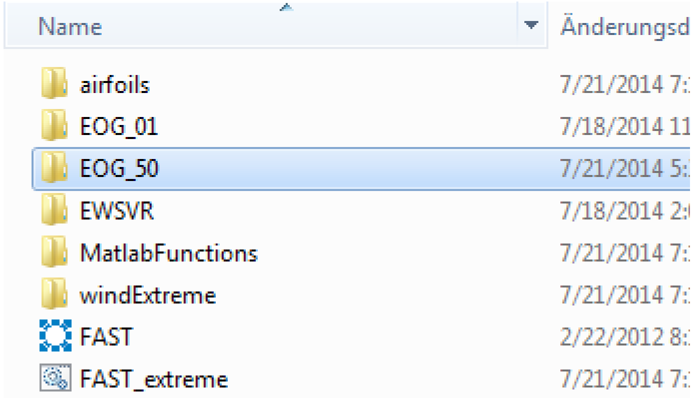

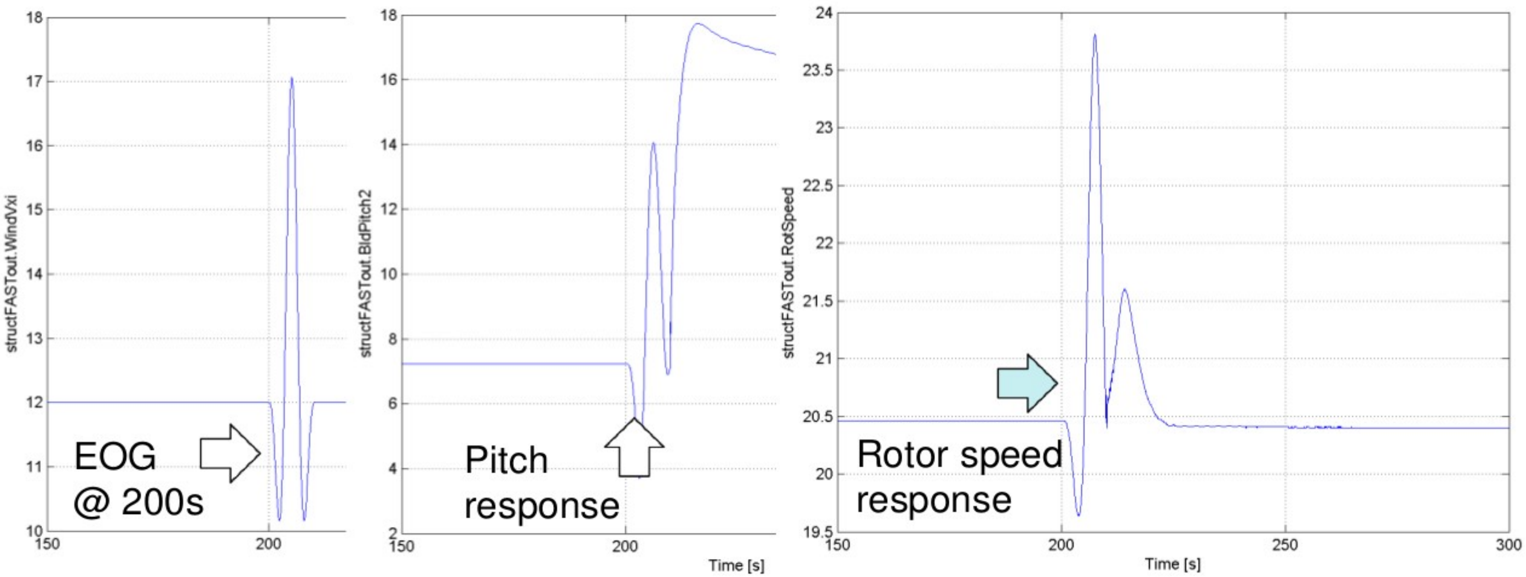

Test case – FAST (5/5)

Rated power

8

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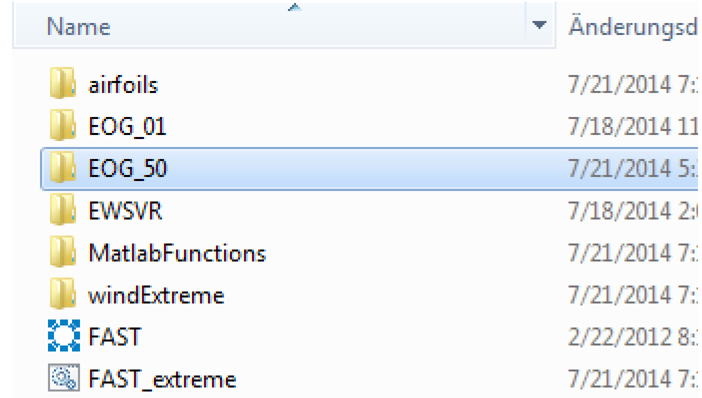

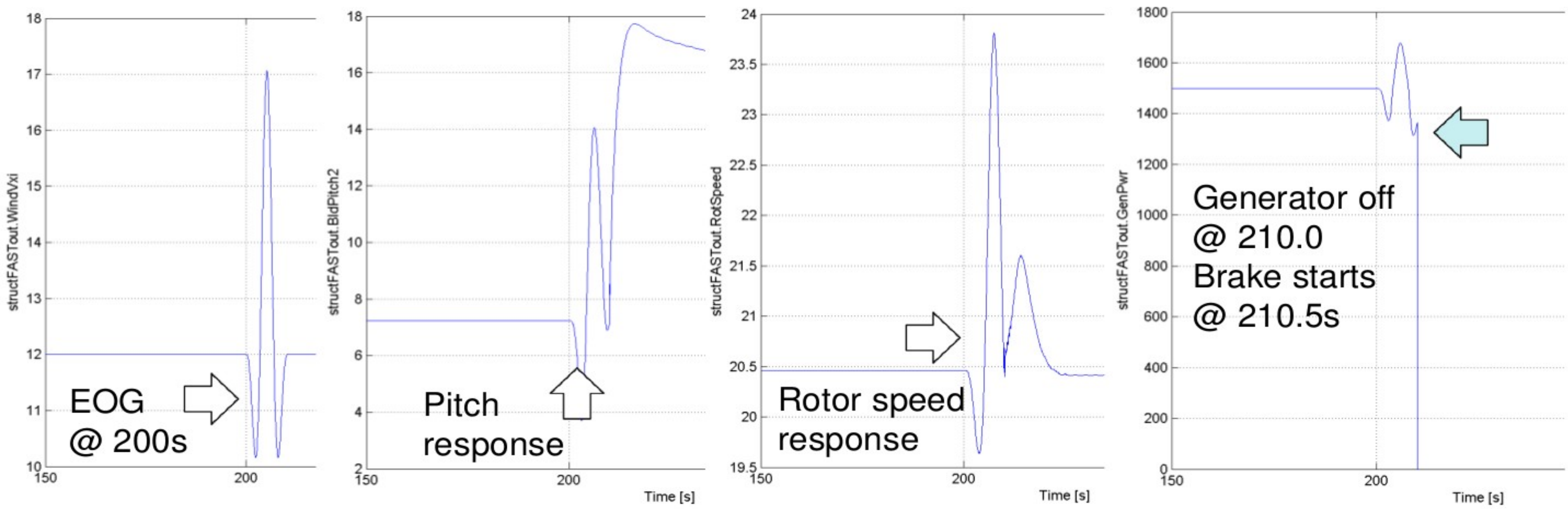

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Test case – FAST (5/5)

Rated power

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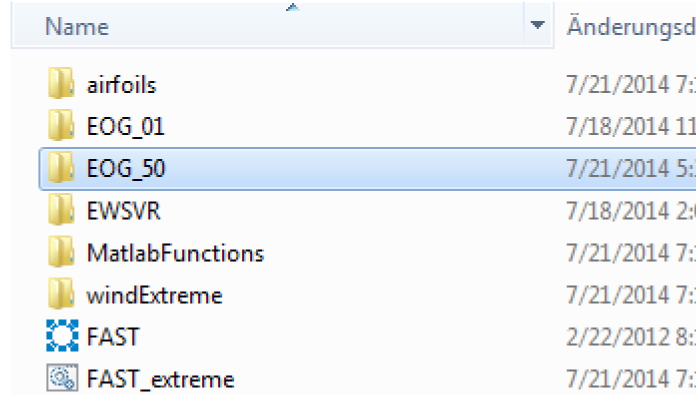

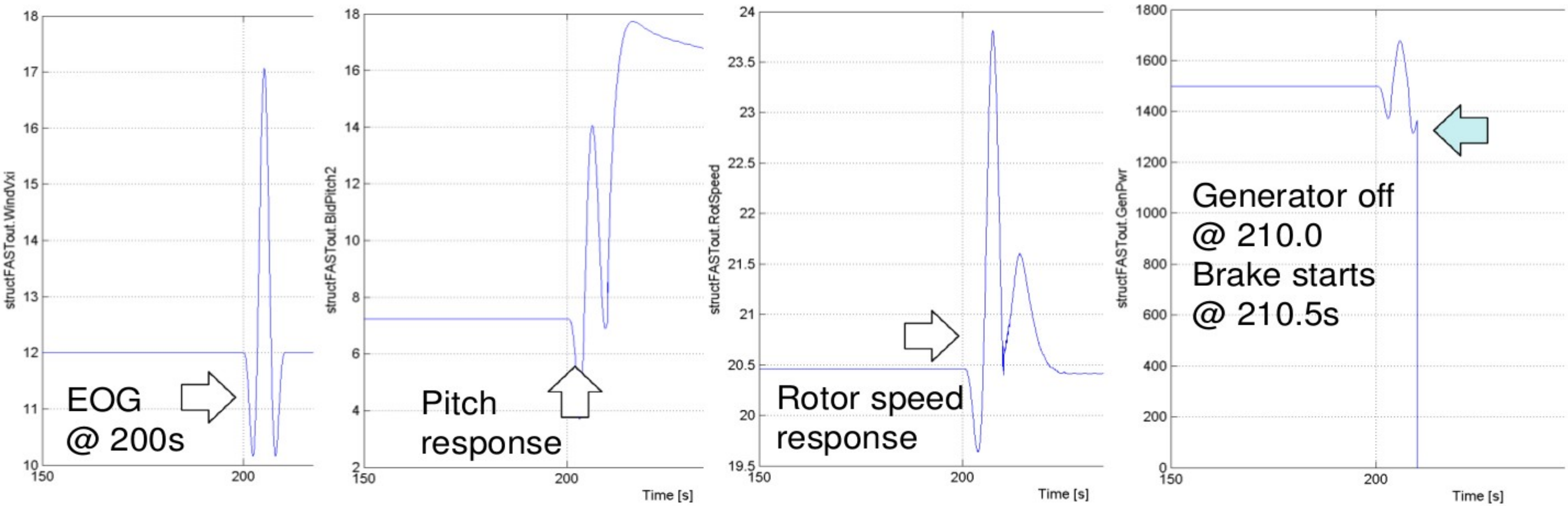

Note:

update brake torque in FAST input file *.fst: HSSBrTqF >> VS_RtTq

```
210.0       TimGenOf     - Time to turn off the generator (s) [u:
   1        HSSBrMode    - HSS brake model {1: simple, 2: user-d
210.5       THSSBrDp     - Time to initiate deployment of the HS:
9214.24     HSSBrTqF     - Fully deployed HSS-brake torque (N-m)
 212.5      HSSBrDT      - Time for HSS-brake to reach full depl
```

Summary

- We reviewed the use of extreme loads
- We reviewed the main combinations that make the design load cases
- We ran two load cases to create an extreme load table

Extreme load in IEC standard

- Extreme operating gust in the IEC standard:

$$V_{\mathrm{Gust}} = Min\left\{1.35\cdot\left(V_{e1}-V_{hub}\right);\ 3.3\cdot\left(\frac{\sigma_1}{1+0.1\cdot\left(\frac{D}{\Lambda_1}\right)}\right)\right\}$$

where

$$\sigma_1 = I_{ref}\left(0.75\cdot v_{hub}+5.6\frac{m}{s}\right)$$

$$\Lambda_1 = \text{turbulence scale parameter} = 42m\ \ for\ z_{hub} \geq 60m$$

$$D = \text{rotor diameter}$$

- Extreme wind speed with 1 year / 50 years recurrence

$$V_{e50}(z) = 1.4\cdot V_{ref}\cdot\left(\frac{z}{z_{hub}}\right)^{0.11}$$

where

$$V_{ref} = reference\ wind\ speed\ according\ to\ IEC\ type\ class$$

$$V_{e1}(z) = 0.8\cdot V_{e50}(z)$$

Extreme load in IEC standard

- Wind speed during extreme operating gust:

$$V(z,t)=\begin{cases} V(z)-0.37\cdot V_{\text{gust}}\sin\left(\dfrac{3\pi\cdot t}{T}\right)\cdot\left(1-\cos\left(\dfrac{2\pi\cdot t}{T}\right)\right) & \text{for } 0\le t\le T \\ V(z) & \text{otherwise} \end{cases}$$

where

$$T=10.5s$$

$$V(z)=V_{hub}\left(\frac{z}{z_{hub}}\right)^{\alpha}\quad with\ \alpha=0.2$$