IEC61400-1 ed. 3
Load Cases, Extremes and Fatigue loads

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Principles

- "specifies essential **design requirements** to ensure the engineering integrity of wind turbines. Its purpose is to provide an appropriate level of protection against damage from all hazards during the planned lifetime"

- "requires the use of a **structural dynamics model** to predict design loads. Such a model shall be used to determine the loads over a range of wind speeds, using the turbulence conditions and other wind conditions defined in…"

- not offshore (then IEC61400-3)

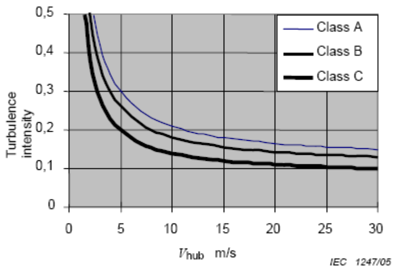
- turbines of all sizes

Turbine classes

- Classification standard

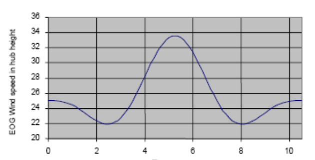
Table 1 – Basic parameters for wind turbine classes[1]

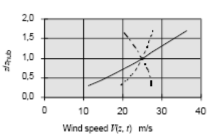
Wind turbine class		I	II	III	S
V_{ref}	(m/s)	50	42,5	37,5	Values specified by the designer
A	I_{ref} (-)	0,16			
B	I_{ref} (-)	0,14			
C	I_{ref} (-)	0,12			

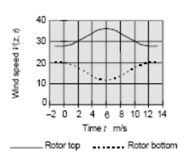


Environmental conditions

- Normal wind conditions
  - Distribution
  - Profile
  - Turbulence model
- Extreme wind conditions
  - Extreme wind speed
  - Extreme operating gust
  - Extreme turbulence model
  - Extreme direction change
  - Gust and direction change
  - Extreme wind shear
- Other conditions (e.g. earthquake…)







Load cases 1

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 $V_{hub} = V_r - 2$ m/s, V_r, V_r +2 m/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 $V_{hub} = V_r \pm 2$ m/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	*

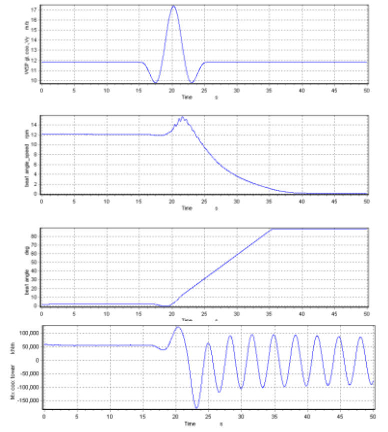
”At least six 10-min stocastic realizations (or a continuous 60min period) shall be required for each mean, hub-height wind speed used in the simulations. However for DLC 2.1,2.2,5.1 at least 12 simulations shall be carried out for each event at the given wind speed.”

Load cases 2

3) Start up	3.1	NWP $V_{in} < V_{hub} < V_{out}$		F	*
	3.2	EOG $V_{hub} = V_{in}$, $V_r \pm 2$ m/s and V_{out}		U	N
	3.3	EDC $V_{hub} = V_{in}$, $V_r \pm 2$ m/s and V_{out}		U	N
4) Normal shut down	4.1	NWP $V_{in} < V_{hub} < V_{out}$		F	*
	4.2	EOG $V_{hub} = V_r \pm 2$ m/s and V_{out}		U	N
5) Emergency shut down	5.1	NTM $V_{hub} = V_r \pm 2$ m/s and V_{out}		U	N
6) Parked (standing still or idling)	6.1	EWM 50-year recurrence period		U	N
	6.2	EWM 50-year recurrence period	Loss of electrical network connection	U	A
	6.3	EWM 1-year recurrence 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 recurrence 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 recurrence period		U	A

Sample load case: EOG with electrical generator fault

```
begin wind ;
  density                 1.225 ;
  wsp                     14  ;
  tint                    0 ;
  horizontal_input        1     ;          0=false, 1=true
  windfield_rotations     0  0.0  0.0 ;    yaw, tilt, rotation
  center_pos0             0.0 0.0 -90.0 ;
  shear_format            3  0.2 ;
  turb_format             0     ;  0=none, 1=mann,2=flex
  tower_shadow_method     1     ;  0=none, 1=potential flow
;  scale_time_start       0 ;
  wind_ramp_factor   0.0 50 0.57 1.0 ;
;
  iec_gust eog 6.248088 0 100 10.5 ;
;
begin tower_shadow_potential;
    tower_offset 0.0 ;
    nsec  2;
    radius      0.0   4.0 ;
    radius    -90.0   1.94 ;
  end tower_shadow_potential;
end wind;
```



Wind:

Rot. speed:

Pitch:

Tower bot.

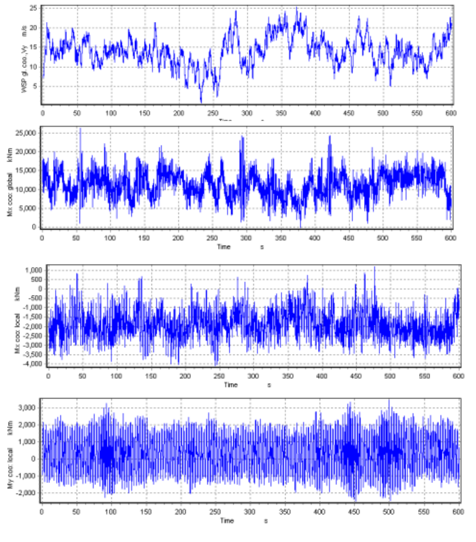
Tilt moment:

iec_gust eog 6.248088 0 100 10.5 ; Type, Vgust, Theta (not used here), t0, T

$$V(z,t)=\begin{cases} V(z)-0{,}37V_{\mathrm{gust}}\sin(3\pi t/T)\left(1-\cos(2\pi t/T)\right) & \text{for } 0\le t\le T \\ V(z) & \text{otherwise}\end{cases}$$

$$V_{\mathrm{gust}}=\mathrm{Min}\left\{1{,}35\left(V_{e1}-V_{\mathrm{hub}}\right);\quad 3{,}3\left(\frac{\sigma_1}{1+0{,}1\left(\frac{D}{\Lambda_1}\right)}\right)\right\}$$

Sample load case: 14 m/s ETM (27%)



Wind

Tower long. bending

Flap

Edge

Analysis of load response time series

- Ultimate load analysis – can the components withstand the largest loads ?
- Fatigue load analysis – can the components withstand the combination of all loads ?
- (Functional requirements, deflections, ...)

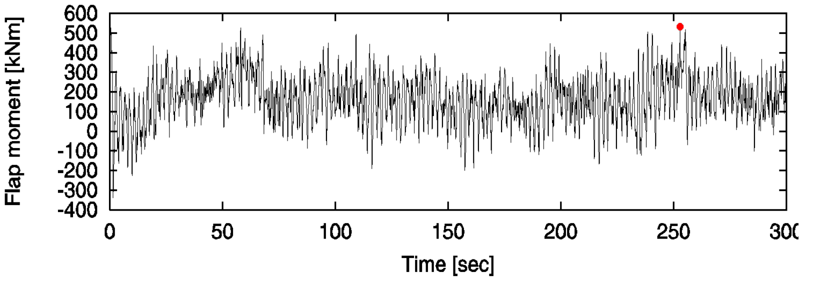
Ultimate load analysis – typical load cases

- Normal production
- Normal production with faults
  - yaw system fault
  - pitch system fault
  - ...
- Extreme conditions
  - extreme wind speed
  - extreme direction change
  - extreme dynamic wind shear
  - electrical faults: Loss of grid
  - ...

Load extrapolation used to extract to 50 year return loads

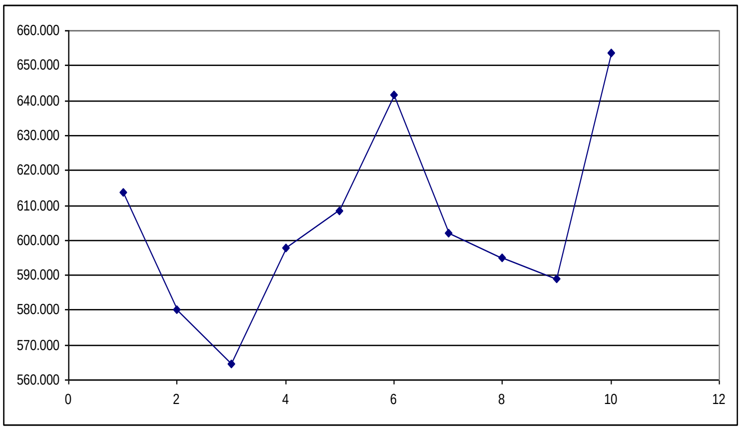
Load extrapolation not used since case is allready at 50 year return level. Mean of maximum used instead.

Extreme loads in normal production



can we imagine a larger load ?

Example, 10 x flapwise moment at different wind series

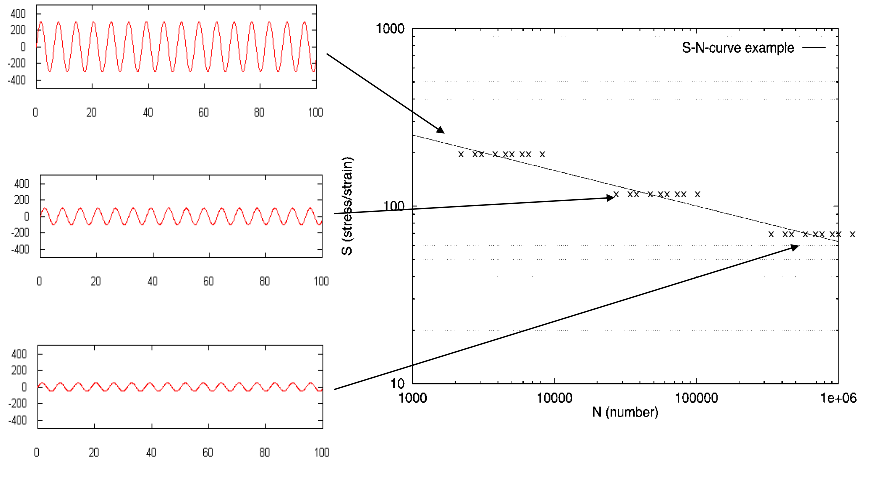


Fatigue analysis

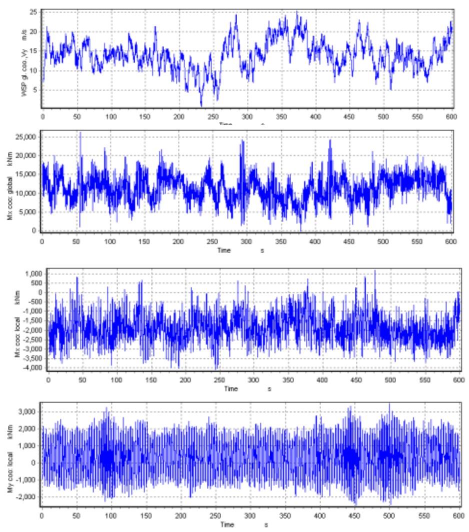
- Each load cycle potentially introduces some degree of damage
- We want to ensure the life time of the wind turbine components when subjected to a life time load collective
- A life time load collective is the combination of all possible load variations during the life time

- The starting point is the material fatigue strength (SN-curves, Wöhlercurves): failure load for a given number of cycles
- We need a counting method since wind turbine loads are time series with varying amplitudes

Material SN-curve (Wöhlercurve)



Sample load case: 14 m/s ETM (27%)



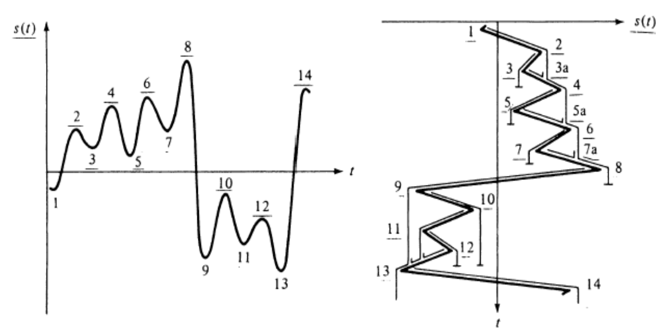
Wind

Tower long. bending

Flap

Edge

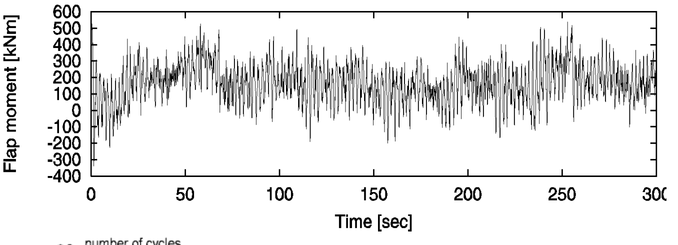
Rainflow counting

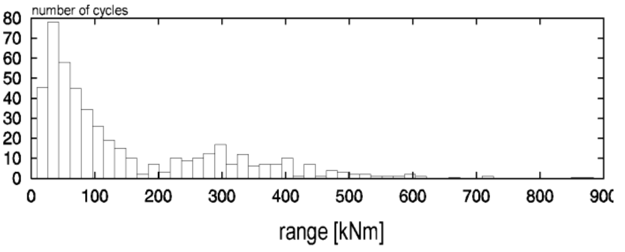


(a) (b)

Matsuishi, M. end Endo, T. 'Fatigue of metals subjected to varying stress' *Paper presented to Japan Soc Mech Engrs* (Jukvoka, Japan, 1968)

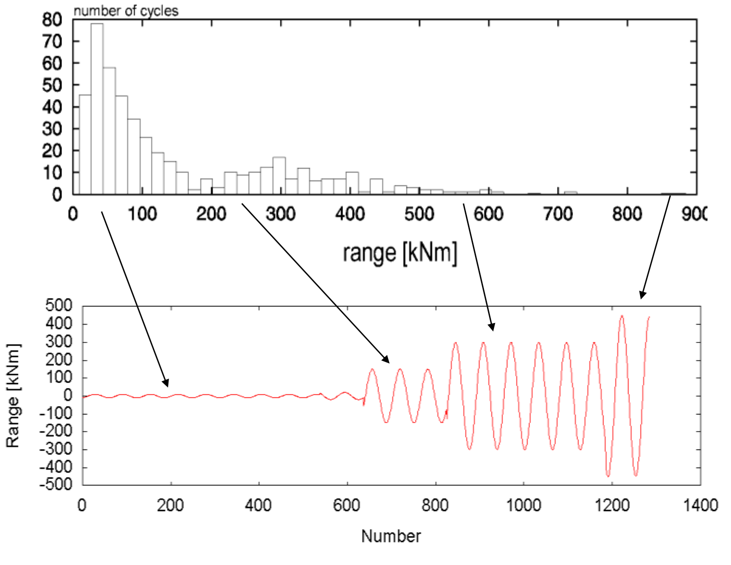
Rainflow counting 1





Fatigue load spectrum for ONE load case

Rainflow counting = rearrangement of time series



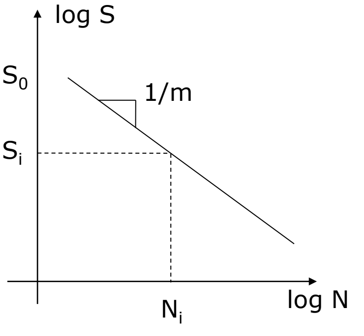
Fatigue damage, Palmgren-Miner

Damage for one variation: $$d_i = \frac{1}{N_i}$$

Damage for more cycles
- with same amplitude: $$D_i = n_i d_i = \frac{n_i}{N_i}$$

SN-curve: $$\log S_0 - \frac{1}{m}\log N_i = \log S_i$$

or: $$N_i = \left(\frac{S_0}{S_i}\right)^m$$



Fatigue damage 2

Damage for more cycles: $$D_i = \frac{n_i}{N_i} = \frac{n_i S_i^m}{S_0^m}$$

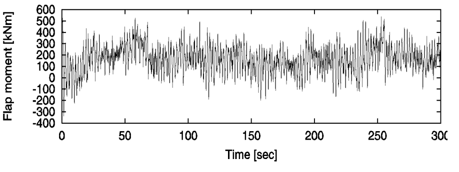
Total damage $$D_{total} = \frac{1}{S_0^m}\sum n_i S_i^m$$

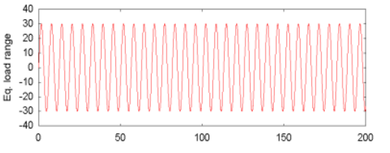
Can we simplify this? $$D_{total} = n_{eq}\frac{S_{eq}^m}{S_0^m}$$

Yes, for a given equivalent number $$S_{eq} = \left(\frac{\sum n_i S_i^m}{n_{eq}}\right)^{1/m}$$

Equivalent load

$$R_{eq} = \left(\frac{\sum n_i R_i^m}{n_{eq}} \right)^{1/m}$$

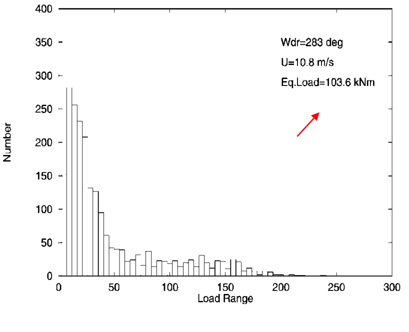


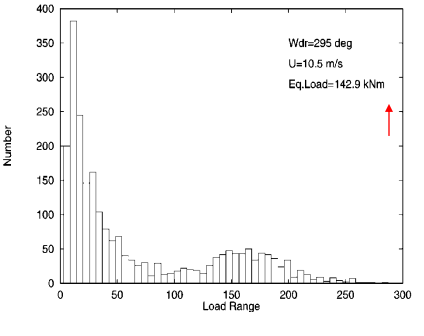


Real time series = Equivalent series

Same fatigue damage

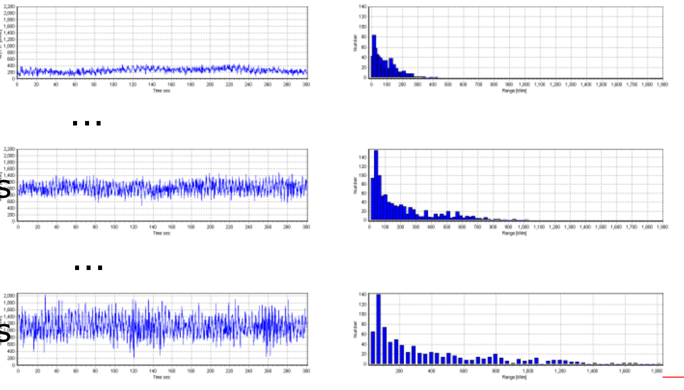
An example of using equivalent loads





For 20 years of operation
Combined fatigue – several load cases

4m/s … 16m/s … 24m/s



x p(U)

x p(U)

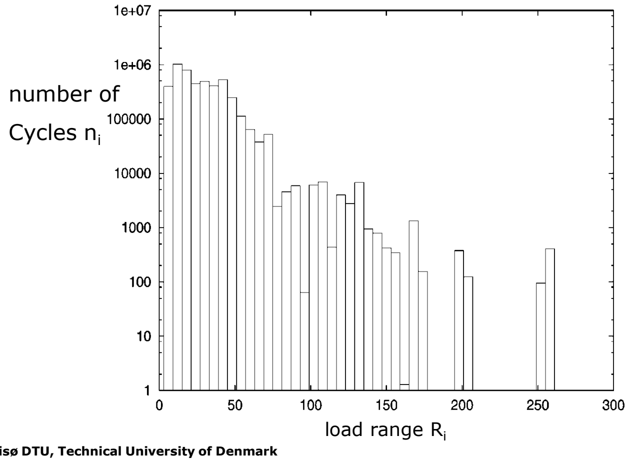
x p(U)

Σ all LC's

Life time load spectrum

Fatigue load spectra from different load cases combines

- and the actual probability is used as weight



Life time equivalent load

From load spectrum:

$$\boxed{L_{eq} = \left(\frac{\sum n_{L,i} R_{L,i}^m}{n_{eq,L}} \right)^{1/m}}$$

From allready calculated eq. loads:

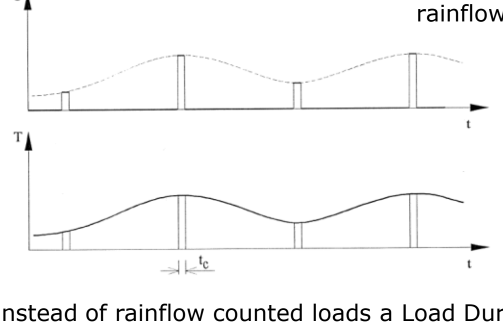
$$D_L = \int_{loadcases} R_{eq}(U)^m n_{eq} p(U) n_T dU$$

$$D_L = n_{eq,L} L_{eq}^m$$

$$\boxed{L_{eq} = \left[\frac{\int R_{eq}(U)^m n_{eq} p(U) n_T dU}{n_{eq,L}} \right]^{1/m}}$$

Equivalent loads for machinery components

Since machinery components as bearings, gear teeths, gear shafts etc. experience one peak load pr revolution, the duration of loads are more important than the rainflow counted loads.



$$L_{eq} = \left(\frac{\sum n_i L_i^m}{n_{eq}} \right)^{\frac{1}{m}}$$

Instead of rainflow counted loads a Load Duration spectrum LDD is used. Number of load cycles are replaced with number of hours. Can be recalculated to number of cycles for the individual shafts.

Palmgren - Miner summation

$$PM = \sum \frac{n_i^{load}}{N_i^{SN-curve}}$$

- PM<1 : the component can withstand the load
- PM>1 : the component fails

Another method is to apply a factor of the loads, recalulate the load spectrum until PM=1. The factor shows how much loads can be increased before 20 years of life time is used.