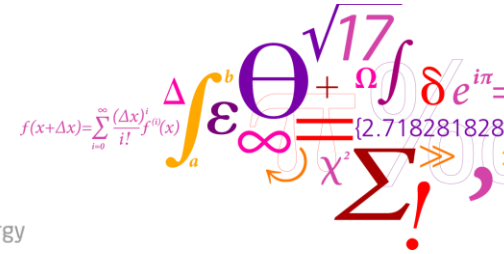
IEC61400-1 ed. 3
Load Cases, Extremes and Fatigue loads



Risø DTU
National Laboratory for Sustainable Energy

Scope

- "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

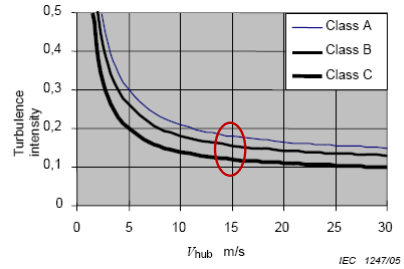
Turbine classes

- 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
A	I_{ref} (-)	0,16			specified
B	I_{ref} (-)	0,14			by the
C	I_{ref} (-)	0,12			designer

I_{ref}: the expected value of the TI at 15m/s

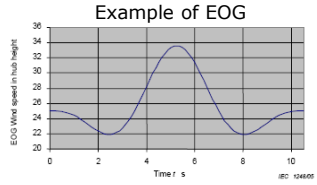


Wind conditions

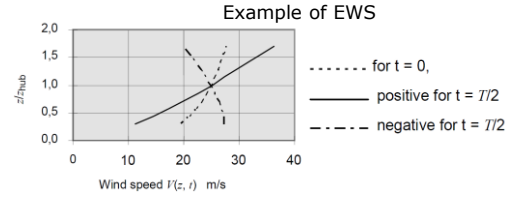
- Normal wind conditions
  - Wind distribution
  - Normal wind profile model (NWP): $V(z) = V_{hub}(z / z_{hub})^{\alpha}$
  - Normal turbulence model (NTM): $TI = \sigma_1 / V_{hub}$

    $where \quad \sigma_1 = I_{ref}(0.75V_{hub} + b); \; b = 5.6 m/s$
- Extreme wind conditions
  - Extreme wind speed model (NWM)
  - Extreme operating gust (EOG)
  - Extreme turbulence model (ETM)
  - Extreme coherent gust with direction change (ECD)
  - Extreme wind shear (EWS)

Example of EOG



Example of EWS



- 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	*
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

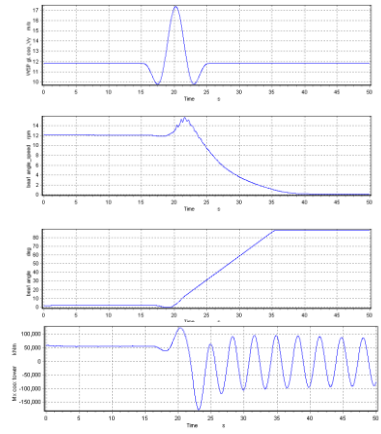
Load cases 2

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

"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 **twelve** simulations shall be carried out for each event at the given wind speed."

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

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

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

Extreme wind condition with HAWC2

	iec_gust	Gust generator according to IEC 61400-1 1. Gust type 'eog' = extreme operating gust $u(z,t)=u(z,t)-0.37A\sin\left(\frac{3\pi(t-t_0)}{T}\right)\left(1-\cos\frac{2\pi(t-t_0)}{T}\right)$ 'edc' = extreme direction change $\theta(t)=0.5\varphi_0\left(1-\cos\left(\frac{\pi(t-t_0)}{T}\right)\right)$ 'ecg' = extreme coherent gust $u(z,t)=u(z,t)+0.5A\left(1-\cos\left(\frac{\pi(t-t_0)}{T}\right)\right)$ 'ecd' = extreme coherent gust with dir. change $u(z,t)=u(z,t)+0.5A\left(1-\cos\left(\frac{\pi(t-t_0)}{T}\right)\right)$ $\theta(t)=0.5\varphi_0\left(1-\cos\left(\frac{\pi(t-t_0)}{T}\right)\right)$ 'ews' = extreme wind shear $d=\sqrt{y_M^2+z_M^2}$ $u(z,t)=u(z,t)+d\,A\left[1-\cos\left(\frac{2\pi(t-t_0)}{T}\right)\right]\cos\left(\arctan 2(y^M,-z^M)-\varphi_0\right)$ even though the 'ews' expressions do not match the expressions in the standard completely, it gives identical results provided a mutual power law shear is used and the A parameter is set to $A=\frac{2.5+0.2\beta\sigma_1\left(\frac{D}{\Lambda_1}\right)^{\frac{1}{2}}}{D}$ and the parameter φ_0 is set to 0, 90, 180, 270 [deg] respectively. 2. Amplitude A [m/s] 3. Angle φ_0 [deg] 4. Time start, t_0 [m/s] 5. Duration T [m/s]

Manual 4-3, 47page

Analysis of load response time series

- Ultimate load analysis – whether the components withstand the largest loads or not.
- Fatigue load analysis – whether the components withstand the combination of all loads or not.
- (Functional requirements, deflections, ...)

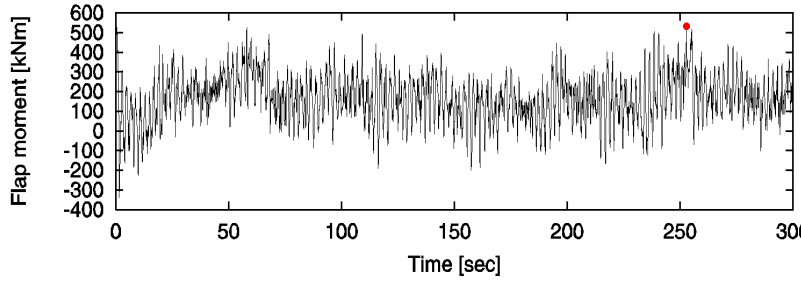
Ultimate load analysis – typical load cases

- 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

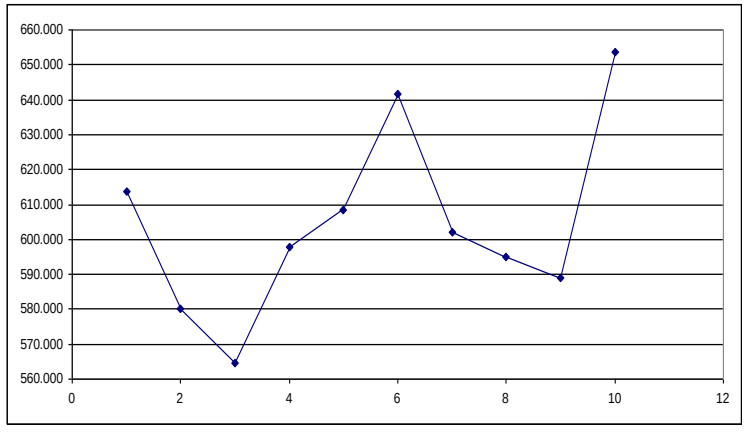
Load extrapolation not used since case is allready at 50 year return level. Mean of maximum used instead.

Extreme loads in normal production



can we imagine a larger load ?

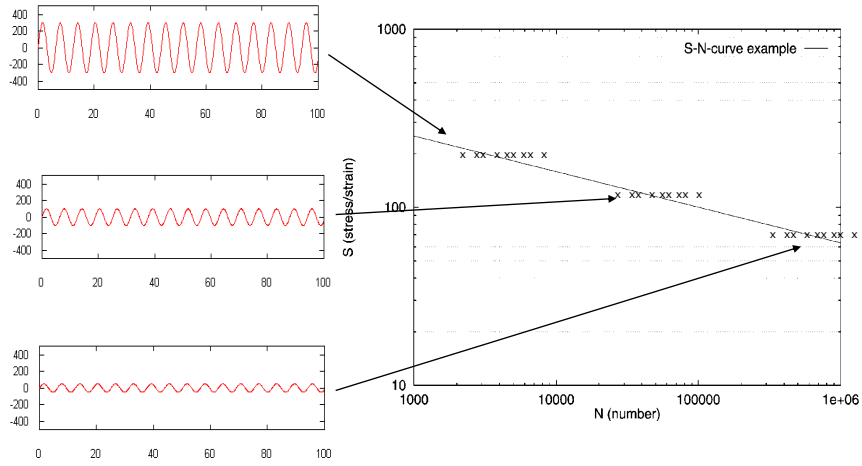
Example, 10 x flapwise moment at different wind series



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
- S-N curves are derived from tests on sample of the material where **a regular sinusoidal stress** is applied

Material SN-curve (Wöhler curve)



Fatigue damage, Palmgren-Miner

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

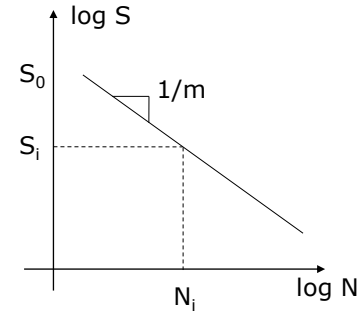
Damage for more cycles (with same amplitude)

$$D_i = n_i d_i = \frac{n_i}{N_i}$$

where n_i is the number of applied load cycles of type i (S_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

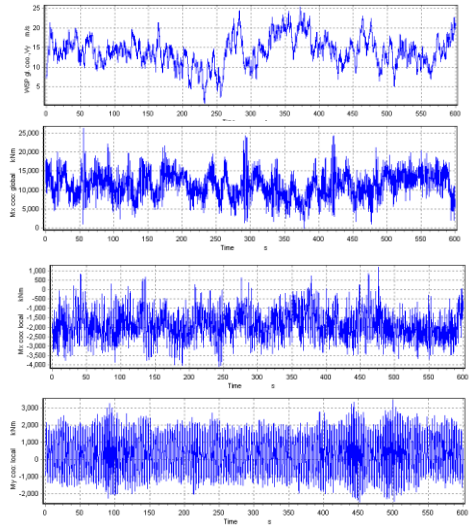
Damage for more cycles: $D_i = \frac{n_i}{N_i} = \frac{n_i S_i^m}{S_0^m}$

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

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



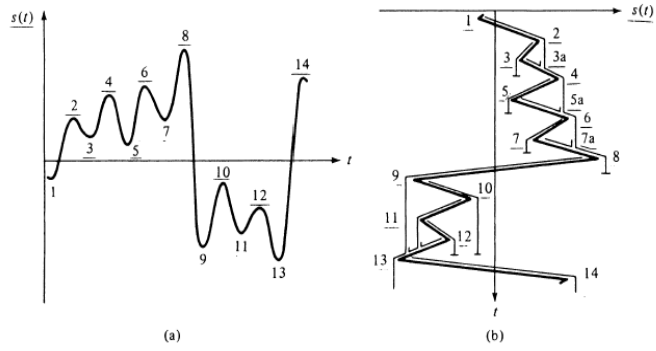
Wind

Tower long. bending

Flap

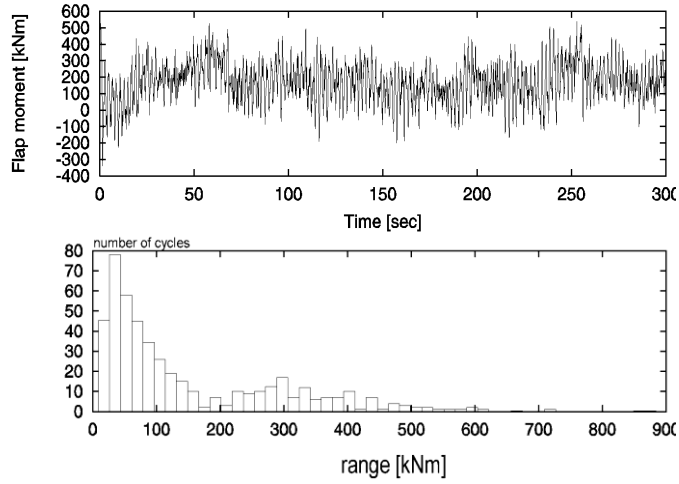
Edge

Rainflow counting



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

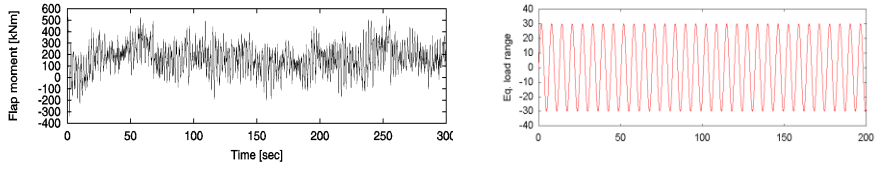
Rainflow counting 1



Fatigue load spectrum for ONE load case

Equivalent load

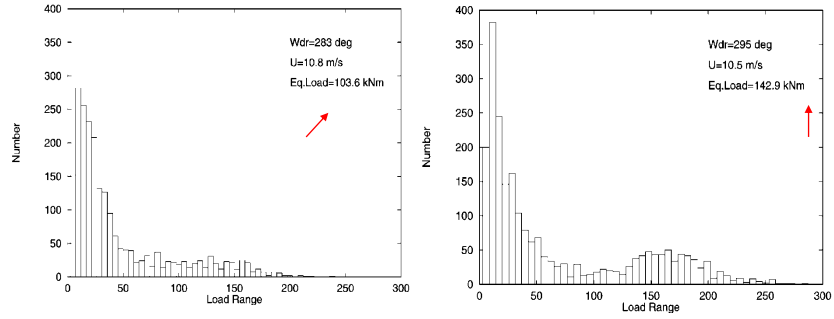
$$S_{eq} = \left(\frac{\sum n_i S_i^m}{n_{eq}} \right)^{1/m} \quad \Rightarrow \quad R_{eq} = \left(\frac{\sum n_i R_i^m}{n_{eq}} \right)^{1/m}$$



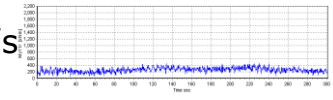
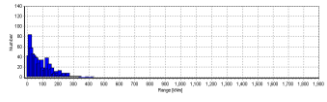
Real time series = Equivalent series

Same fatigue damage

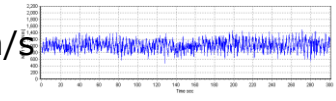
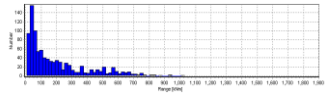
An example of using equivalent loads



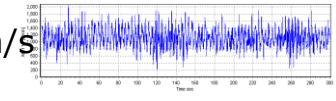
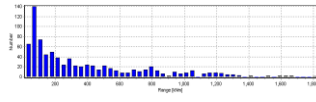
For 20 years of operation
Combined fatigue – several load cases

4m/s   x p(U)

...

16m/s   x p(U)

...

24m/s   x p(U)

Σ all LC's

Life time equivalent load

- Wind speed distribution

✓Often used distribution functions are the Rayleigh, P_R, and the Weibull, P_W, functions.

$$P_R(V_0) = 1 - \exp\left[-\pi\left(V_0 / 2V_{ave}\right)^2\right]$$

$$P_W(V_0) = 1 - \exp\left[-\left(V_0 / C\right)^k\right]$$

$$where\, V_{ave} = \left\{ \begin{array}{c} C\Gamma\left(1 + \frac{1}{k}\right) \\ C\sqrt{\pi}/2, if\ \ k = 2 \end{array} \right\}$$

Equations from IEC standard(61400-1 3rd, 15page)

✓From the Weibull distribution, the probability that the wind speed lies between V_i and V_{i+1} is calculated as

$$P_W(V_i < V_o < V_{i+1}) = P_W(V_{i+1}) - P_W(V_i)$$

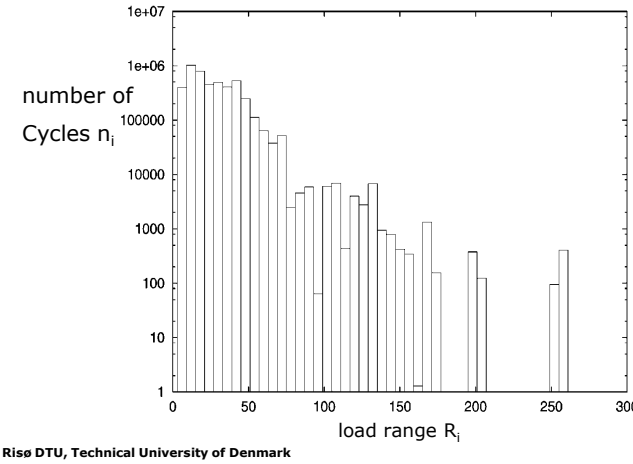
Equations from Aerodynamics of Wind Turibnes 2nd edition, Martin O.L. Hansen book, 57page Eq.(6.48)

And IEC standard 16page

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:

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

From allready calculated eq. loads:

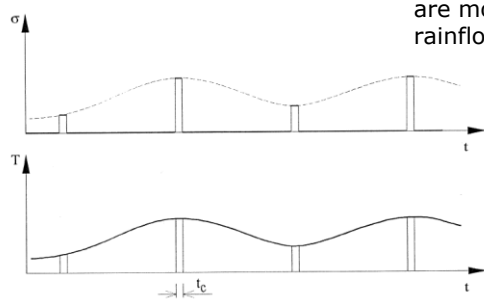
$$D_L = \int_{loadcases} R_{eq}(U)^m n_{eq} p(U) n_T dU$$

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

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

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.