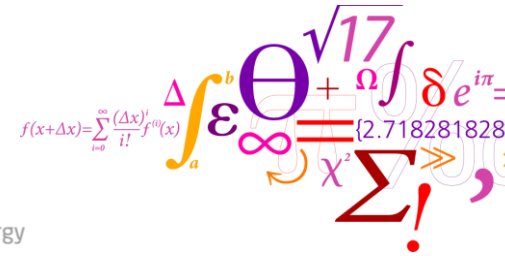
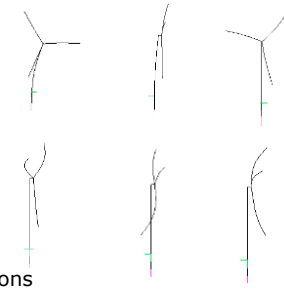
IEC61400-1 ed. 3
Load Cases, Extremes and Fatigue loads



Risø DTU
National Laboratory for Sustainable Energy

Repetition of:
Load considerations.

- Structural dynamics
  - Model the turbine and find the eigenfrequencies
- Aerodynamics
  - Induction
  - Dynamic stall
  - 3D corrections
  - Evaluate power curve
- Control
  - Full dynamic implementation needed
  - Check performance with step changes in wind spe
  - Check performance in turbulent wind.
- Stability
  - Is the turbine dynamic motion stable in all conditions
- Wind
  - Stochastic wind
  - Deterministic wind
- Wake effects
  - Sten Frandsen method (in standard)
  - DWM method (more detailed, but not in standard yet)



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

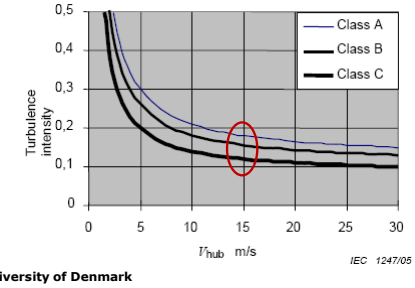
Turbine classes

- Classification standard

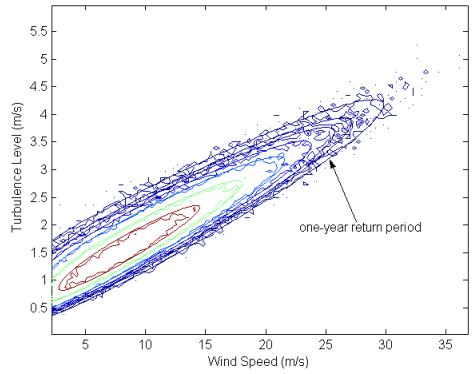
Table 1 – Basic parameters for wind turbine classes[1]

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



The classes are simplifications



PDF of wind speed and sigma_u=f(U)

Fatigue is non-linear and 90% fractile of sigma_u is used

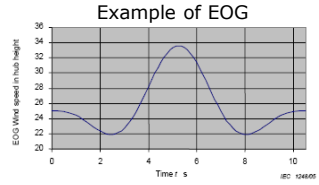
From Moriarty, 2005

Wind conditions

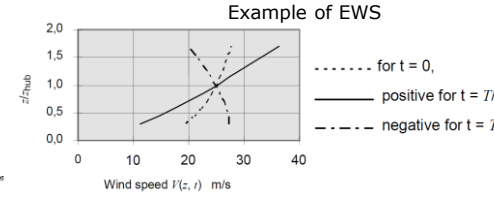
- Normal wind conditions
  - Wind distribution
  - Normal wind profile model (NWP): $V(z) = V_{hub}(z / z_{hub})^{\alpha}$
  - Normal turbulence model (NTM): $TI = \sigma_1 / V_{hub}$

    $where \quad \sigma_1 = I_{ref}(0.75V_{hub} + b); \; b = 5.6 m/s$
- 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

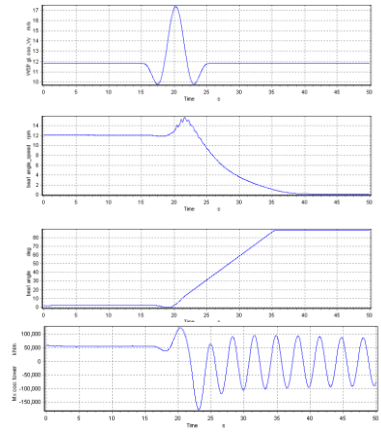
Load cases 2

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

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

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

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, ...)

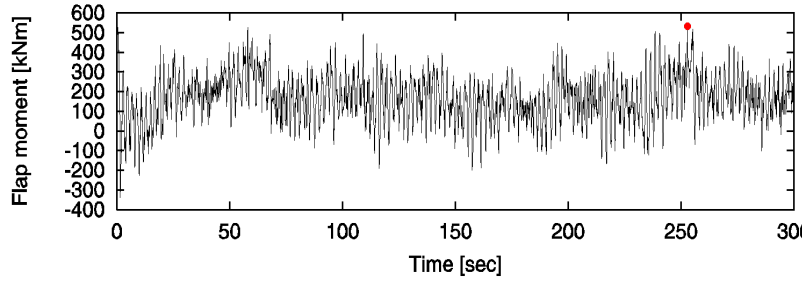
Ultimate load analysis – typical load cases

- 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

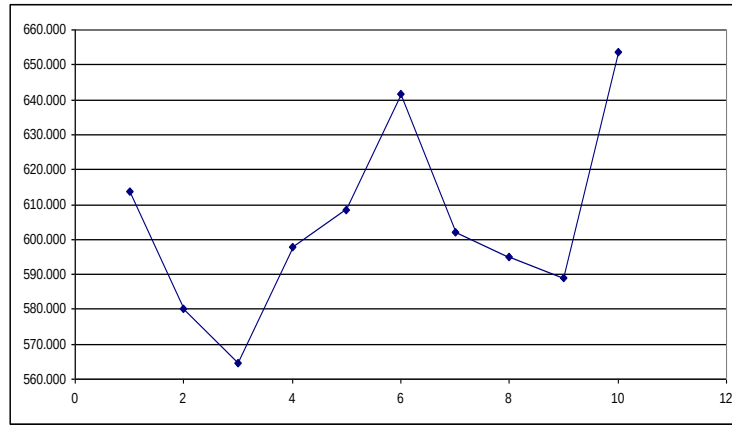
Load extrapolation not used since case is allready at 50 year return level. Mean of maximum used instead.

Extreme loads in normal production



can we imagine a larger load ?

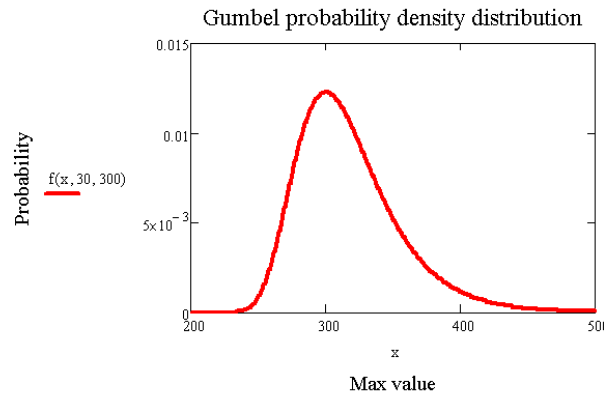
Example, 10 x flapwise moment at different wind series



Extreme values are typically Gumbel distributed

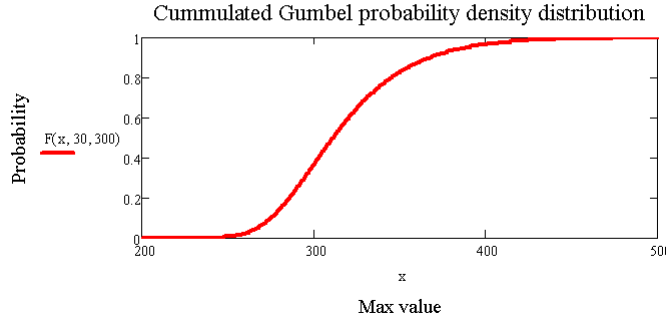
$$f(x,\beta,\mu) := \frac{1}{\beta}\cdot 1\exp\left(-1\cdot\frac{x-\mu}{\beta} - \exp\left(-1\cdot\frac{x-\mu}{\beta}\right)\right)$$

$x := 200, 200.1 .. 500$



The accumulated gumbel distribution

$$F(x,\beta,\mu) := \exp\left(-\exp\left(-1\cdot\frac{x-\mu}{\beta}\right)\right)$$



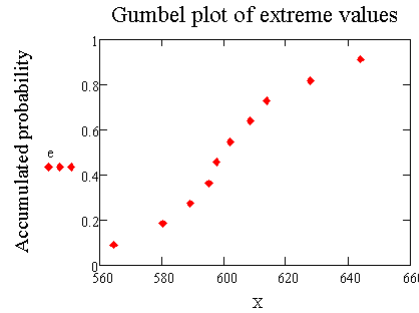
The plotting problem, Gumbel 1958

The problem is the limited number of data available for finding the distributions.

In the cummulative density distribution plot, the y-axis is the cummulative probability, but can also resonably be constructed based on a rank-index

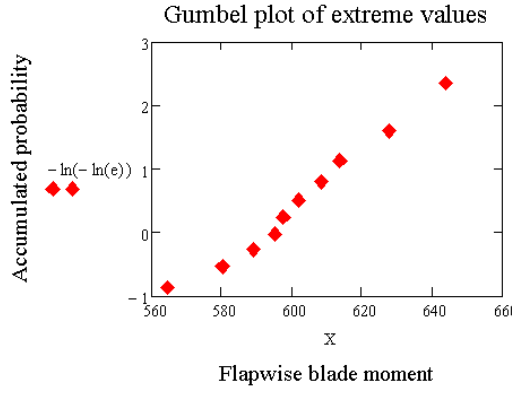
$$e_i = \frac{i}{N+1}$$

$$X := \begin{pmatrix} 564.6 \\ 580.2 \\ 589 \\ 595 \\ 597.7 \\ 602 \\ 608.5 \\ 613.8 \\ 627.6 \\ 643.8 \end{pmatrix} \quad i := \begin{pmatrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \end{pmatrix} \quad e_i := \frac{i}{N+1}$$



The plotting

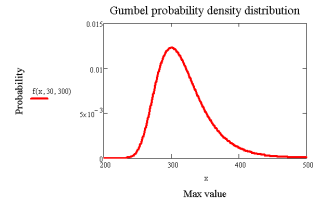
When mapping the y-axis on a –ln(-ln(F(x)) manner, the distribution appears linear



Curve fitting

Several methods exist, where the most simple and crude is based on moment estimation.

$$f(x,\beta,\mu) := \frac{1}{\beta}\cdot\exp\left(-1\cdot\frac{x-\mu}{\beta}-\exp\left(-1\cdot\frac{x-\mu}{\beta}\right)\right) \qquad x := 200, 200.1 .. 500$$



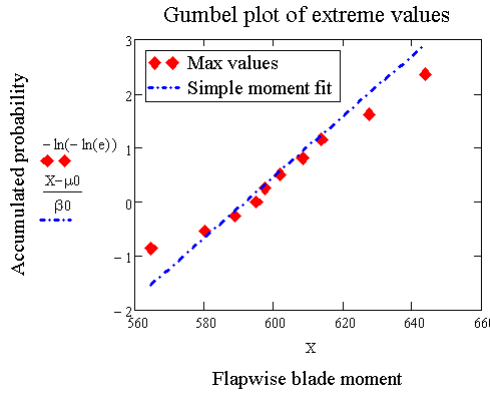
The distribution has a mean value $E(x) = \mu + \beta\gamma$

And a standard deviation $\sigma(x) = \frac{\beta\pi}{\sqrt{6}}$

To which the gumbel parameters can be found

$$\beta = \frac{\sqrt{6}\sigma(x)}{\pi}, \qquad \mu = E(x) - \beta\gamma, \qquad \gamma = 0.5772$$

Fit by moment estimation



Fitting by the probability weighted moment method (PWM), Hosking et. al. 1985

Still simple and well working method.

A new estimator is established

$$b_m = \frac{1}{N}\sum_{i=1}^{N}\frac{(i-1)(i-2)...(i-m)}{(N-1)(N-2)...(N-m)}X_i$$

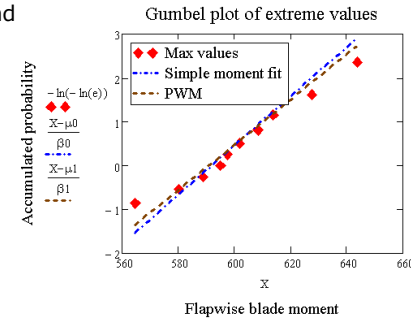
$$e1_j := X_j \cdot \frac{i_j - 1}{N - 1}$$

$$b0 := \mathrm{mean}(X) \qquad b1 := \mathrm{mean}(e1)$$

$$\beta 1 := \frac{2 \cdot b1 - b0}{\ln(2)} \qquad \mu 1 := b0 - \gamma \cdot \beta 1$$

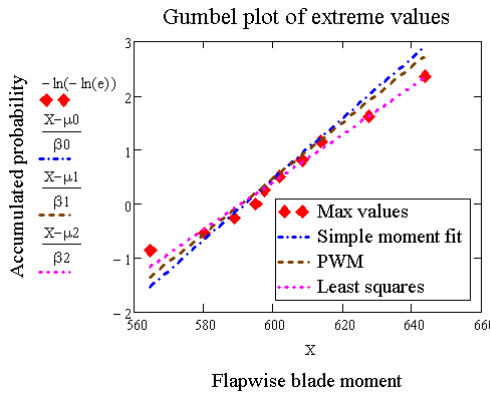
And the gumbel parameters are found

$$\beta = \frac{2b_1 - b_0}{\ln(2)}, \qquad \mu = b_0 - \gamma\beta$$



Other methods

Finally there is the method of least squares and/or maximum likelyhood methods.



$$linefit := line(-\ln(-\ln(e)), X)$$

$$\beta 2 := linefit_1 \qquad \mu 2 := linefit_0 \qquad linefit = \begin{pmatrix} 591.031 \\ 22.594 \end{pmatrix}$$

Extrapolation of results to a 50year return period

The probability P_f can be found for the return period R based on the time length for the used block length

$$P_f = 1 - \exp\left(\frac{-t}{R}\right), \quad t = 10\,\text{min}, \quad R = 50\,years \quad P_f = 3.8E-7$$

The 50 year load can (provided the simulated loads case is the only occuring) be found based directly on the gumbel parameters fitted for this windspeed.

$$x_{50y} = -\beta \ln(-\ln(P_f)) + \mu$$

In the design situation, several different wind speeds V and the Weibull distribution p(V) need to be taken into account

$$P(M_{10\text{min}} > x) = 1 - F(x) = \sum_V \left(1 - F(x|V)\right) p(V)$$

Load extrapolation

Return period probability

$Pf := 3.8 \cdot 10^{-7}$

Weibull probability

$Pv := 0.12$

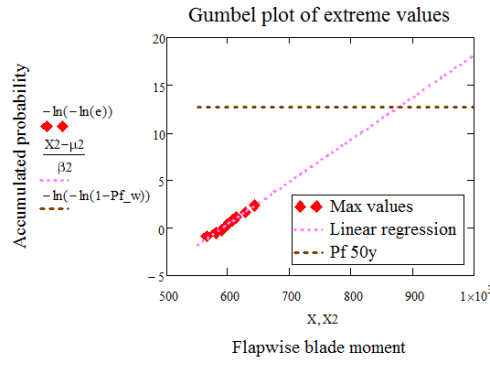
$X2 := 550 .. 1000$

$Pf_w := \frac{Pf}{Pv}$

$X50y := -\beta 2 \cdot \ln(-\ln(1 - Pf_w)) + \mu 2$

$X50y = 877.131$

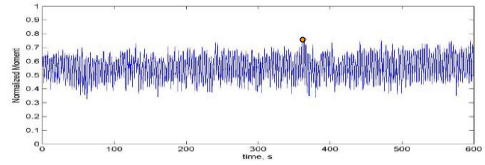
$\frac{X50y}{\max(X)} = 1.362$



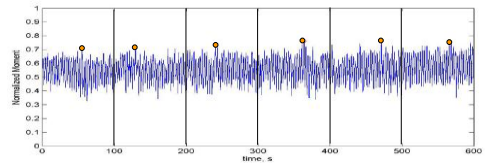
Selection method for finding the maximum values in time simulations

Extreme values must be independent

Global maxima

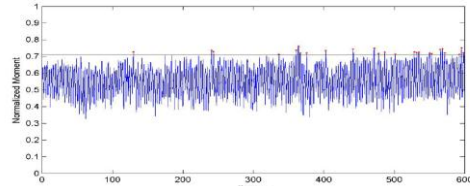


Block maxima



Peak over threshold

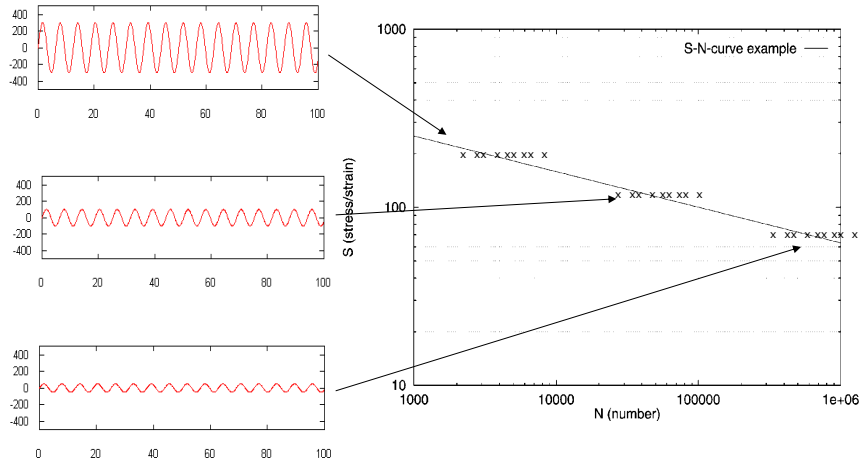
(not recommended)



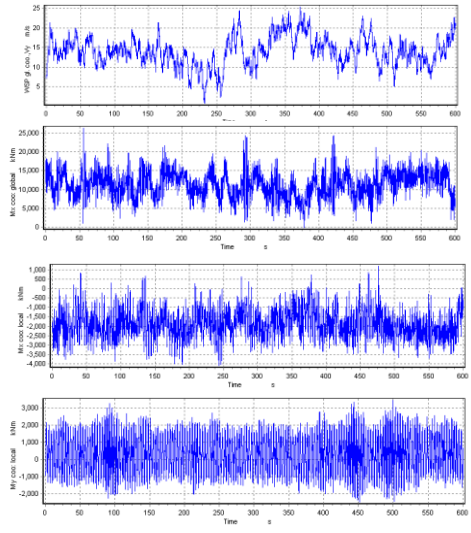
Fatigue analysis

- 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)



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



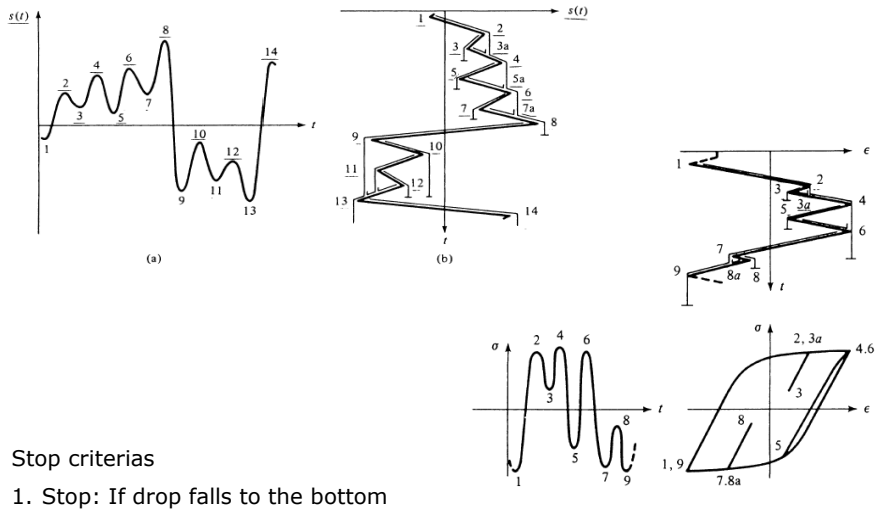
Wind

Tower long. bending

Flap

Edge

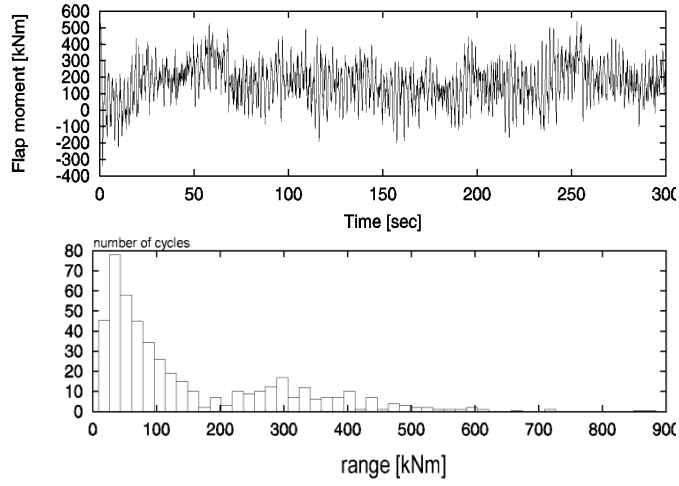
Rainflow counting



Stop criterias

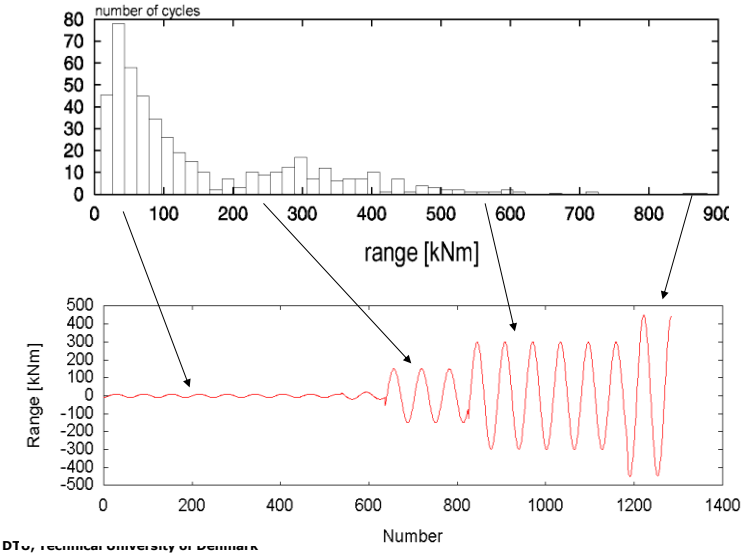
1. Stop: If drop falls to the bottom
2. Stop: If path meets a previous drops path

Rainflow counting 1



Fatigue load spectrum for ONE load case

Rainflow counting = rearrangement of time series



Fatigue damage

Damage for one variation:

$$d_i = \frac{1}{N_i}$$

Damage for more cycles
- with same amplitude:

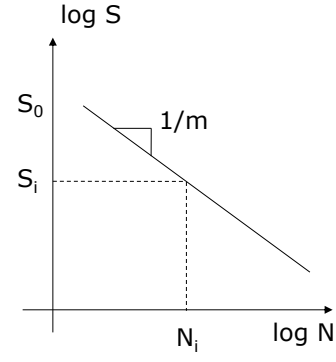
$$D_i = n_i d_i = \frac{n_i}{N_i}$$

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: $$D_i = \frac{n_i}{N_i} = \frac{n_i S_i^m}{S_0^m}$$

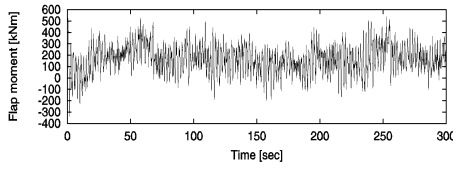
Total damage $$D_{total} = \frac{1}{S_0^m} \sum n_i S_i^m$$

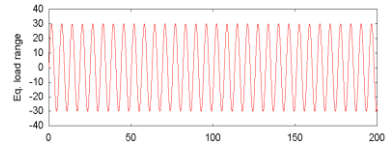
Can we simplify this? $$D_{total} = n_{eq} \frac{S_{eq}^m}{S_0^m}$$

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

Equivalent load

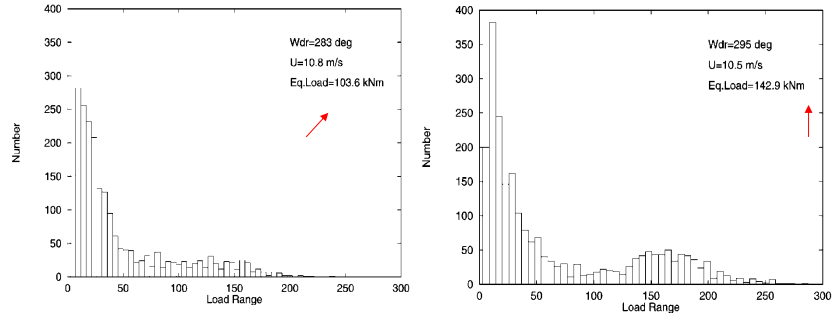
$$R_{eq} = \left(\frac{\sum n_i R_i^m}{n_{eq}} \right)^{1/m}$$



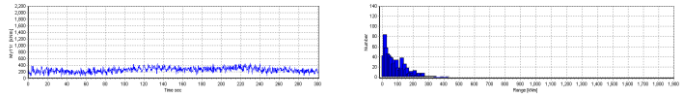


Real time series = Equivalent series

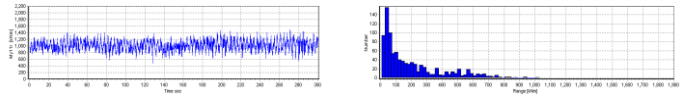
An example of using equivalent loads



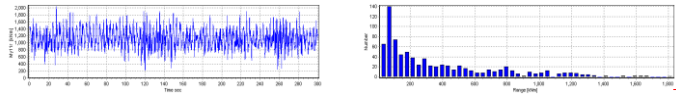
Combined fatigue – several load cases

4m/s  x p(U)

...

16m/s  x p(U)

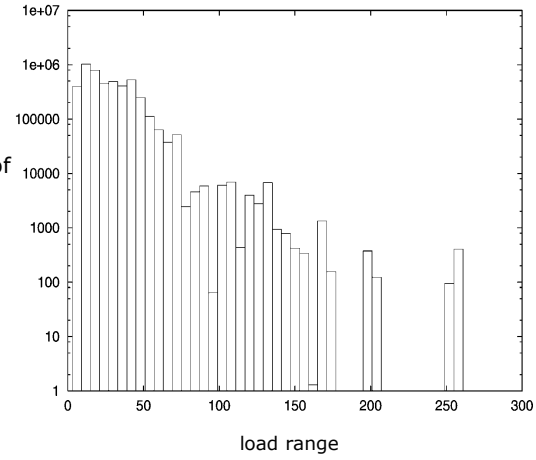
...

24m/s  x p(U)

Σ all LC's

Life time load spectrum 20years

number of cycles



$(R_{L,i}; n_{L,i})$

Life time equivalent load

From allready calculated eq. lo

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

From load spectrum:

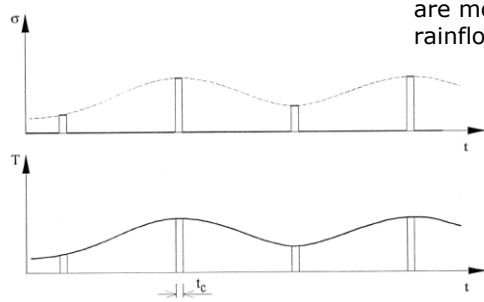
$$D_L = n_{eq,L} L_{eq}^m$$

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

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

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.