EN4103 – Renewable Energy Design
a.y. 2018/19
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Wind Turbine Tower Design

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(part of this presentation has been adapted from Burton, 2015)

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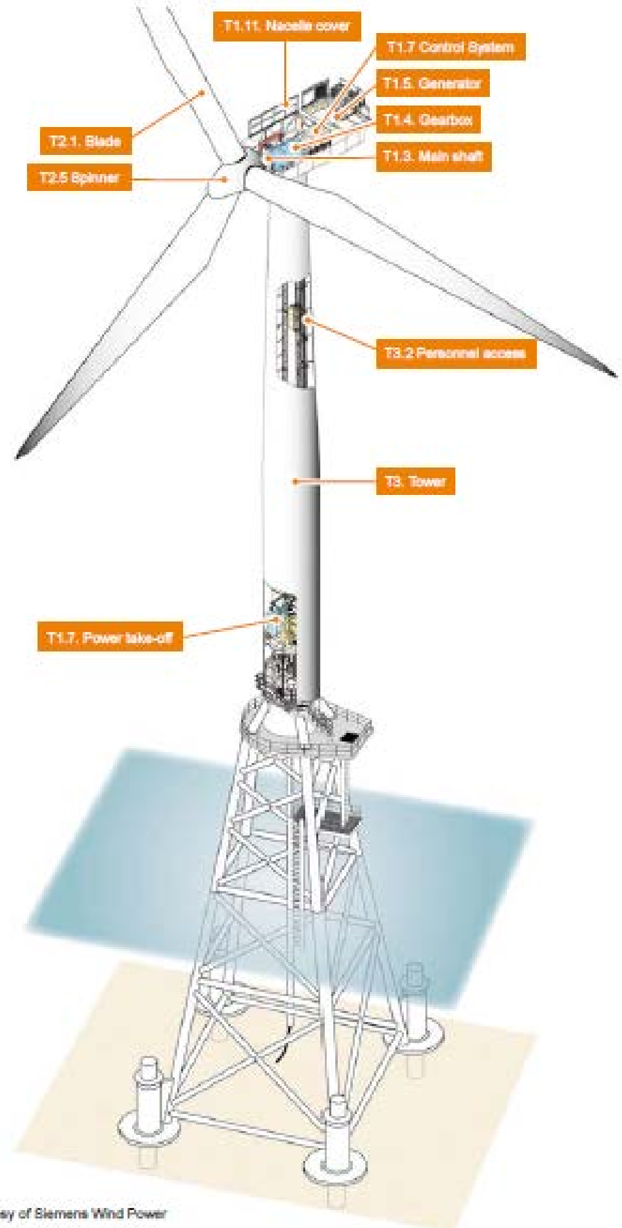
Scheme of an offshore wind turbine



Reproduced courtesy of Siemens Wind Power

Tower design concept

- **STEEL**
  - **Tubular**
    - Free-standing, tapered (most common, by far)
    - Guyed
    - Braced
  - **Lattice**
    - Free-standing, tapered
    - Guyed
- **CONCRETE**
  - **Tubular**
    - Normally prestressed

References

- **Books**
  - Hau (2006) Wind Turbine Fundamentals
  - Burton et al (2014) Wind Energy Handbook
  - EN2300 Design Notes
- **Standards**
  - Eurocode 3, National Annex (BS EN 1993)
  - DNV-GL code of practice/guidelines on wind turbines
- **Software**
  - Bladed 4.4 Educational, Garrad Hassan
- **Reports**
  - Rawlinson-Smith (2004) Load calculations for a generic 1.5 MW wind turbine…

Design Constraints

- Ultimate limit state (ULS)
  - Plastic limit (tower, joints)
  - Buckling (tower)
  - Fatigue (tower, joints)
- Serviceability limit state (SLS)
  - Slip resistance check (joint)
- Avoidance of resonance (vibration frequency)
- Blade clearance
- Transportability

Standards

- **EN 1993-1-6:2007** DESIGN OF STEEL STRUCTURES – STRENGTH AND STABILITY OF SHELL STRUCTURES
- **EN 1993-1-8:2007** DESIGN OF STEEL STRUCTURES – DESIGN OF JOINTS
- **EN 1993-1-9:2007** DESIGN OF STEEL STRUCTURES – FATIGUE
- See BS National Annexes

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Load Analysis

- **Wind Turbine Loads**

  Inertia and gravity loads

  Aerodynamic loads

  Operational loads

  Other loads (wake, impact, ice …)

- **Load Analysis**

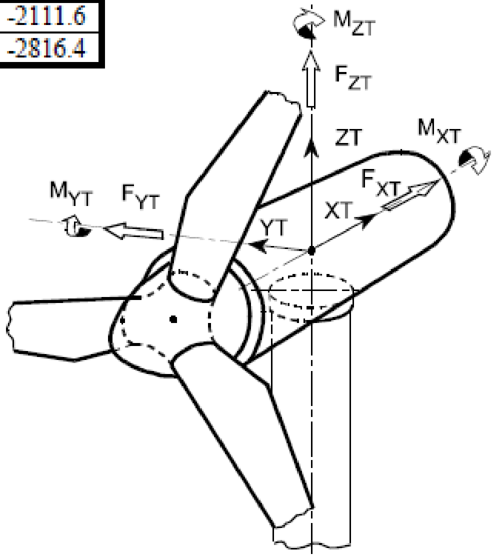
  Bladed Software

  Indications can be suggested also by scaling from other WT designs

Load Analysis

		Load case	Mx kNm	My kNm	Mxy kNm	Mz kNm	Fx kN	Fy kN	Fxy kN	Fz kN
Mx	Max	6.1k	59022	10049	59871	1061.2	230.2	-808.5	840.6	-2600.2
Mx	Min	6.1o	-49749	15133	52000	-1126.2	263.3	672.8	722.5	-2689.1
My	Max	1.5c	1173.3	37424	37442	291.3	482.6	0.50	482.6	-2778.2
My	Min	1.3f	-7170.6	-44470	45044	-313.5	-509.2	100.5	519.1	-2707.4
Mxy	Max	6.1k	58988	11721	60141	1295.1	284.3	-817.2	865.2	-2600.5
Mxy	Min	1.1a	3.5	7.0	7.8	38.8	19.3	2.3	19.4	-2731.9
Mz	Max	2.2a	3670.0	4567.6	5859.4	3254.4	76.8	-30.6	82.7	-2267.6
Mz	Min	1.1f	-8139.8	1158.2	8221.8	-2713.1	48.2	128.3	137.1	-2714.7
Fx	Max	6.1h	-17442	32747	37102	35.6	616.3	251.1	665.5	-2653.8
Fx	Min	1.3f	-7170.6	-44470	45044	-313.5	-509.2	100.5	519.1	-2707.4
Fy	Max	6.1o	-49749	15133	52000	-1126.2	263.3	672.8	722.5	-2689.1
Fy	Min	6.1k	58988	11721	60141	1295.1	284.3	-817.2	865.2	-2600.5
Fxy	Max	6.1k	58988	11721	60141	1295.1	284.3	-817.2	865.2	-2600.5
Fxy	Min	1.1a	64.7	-1255.6	1257.2	15.3	0.17	0.21	0.27	-2740.9
Fz	Max	7.1c70	1844.8	12494	12629	-44.5	254.5	11.9	254.7	-2111.6
Fz	Min	1.1e	3070.6	12526	12897	-112.6	188.2	-31.2	190.8	-2816.4

Table 5.4 - Ultimate Loads: Tower at 0.00m



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Materials

Table 1 – Steel properties

Element	Standard and steel grade	Nominal thickness of the element t [mm]			
		$t \leq 40$ mm		40 mm $< t \leq 80$ mm	
		f_y	f_u	f_y	f_u
		[MPa]	[MPa]	[MPa]	[MPa]
Flange	S355	355	510	335	470
Tower	S355	355	510	335	470

According to EN1993-1-8:2005 [5] bolt class and relevant properties are reported below:

Table 2 – Bolt properties

Bolt class	f_{yb}	f_{ub}
	[MPa]	[MPa]
8.8	640	800

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Partial Factors

- **EC-3: Ultimate LS**

$\gamma_{G_1} = 1,35$ Permanent loads

$\gamma_{Q_1} = 1,50$ Variable loads

Material, resistance	γ_{M0}	1,00
Mat., buckling	γ_{M1}	1,10
Mat., bolts	γ_{M2}	1,25

- **EC-3: Serviceability LS**

$\gamma_{G_1} = 1,00$

$\gamma_{Q_1} = 1,00$

Mat., bolts	$\gamma_{M3,res}$	1,10

- **DNV-GL guidelines**

Type	PSFL
Abnormal safety factor Load case 2.2 and 7.1	1.10
Normal and extreme safety factor All other load cases	1.35
Transport and erection safety factor Load case 8.1	1.5

ULS: Plastic limit (tower)

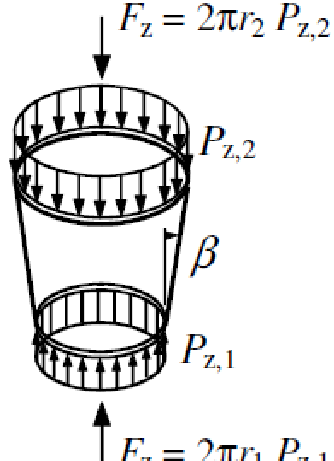
Reference: **EC3-1-6**, sect 4.1 etc (tower),

Annex A

$$\sigma_{eq,Ed} = \sqrt{\sigma_{z,Ed}^2 + 3\tau_{z\theta,Ed}^2}$$

$$\sigma_{\mathrm{eq,Ed}} \leq f_{\mathrm{eq,Rd}}$$

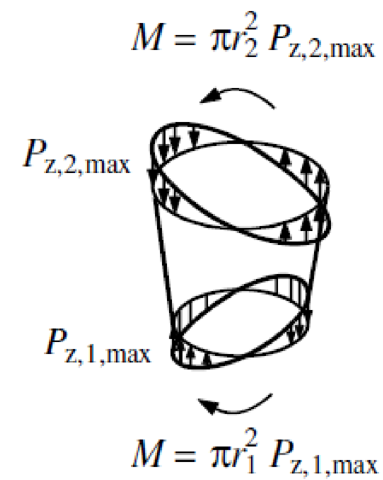
A.3.1 Uniform axial load



$$\sigma_x = -\frac{F_z}{2\pi r t \cdot \cos\beta}$$

$$\sigma_\theta = 0$$

A.3.2 Axial load from global bending



$$\sigma_{x,\max} = \pm\frac{M}{\pi r^2 t \cdot \cos\beta}$$

$$\sigma_\theta = 0$$

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ULS: Plastic limit (joints)

Reference: **EC3-1-8**

Table 3.2: Categories of bolted connections

Category	Criteria	Remarks
Shear connections		
A bearing type	$F_{v,Ed} \leq F_{v,Rd}$ $F_{v,Ed} \leq F_{b,Rd}$	No preloading required. Bolt classes from 4.6 to 10.9 may be used.
B slip-resistant at serviceability	$F_{v,Ed.ser} \leq F_{s,Rd,ser}$ $F_{v,Ed} \leq F_{v,Rd}$ $F_{v,Ed} \leq F_{b,Rd}$	Preloaded 8.8 or 10.9 bolts should be used. For slip resistance at serviceability see 3.9.
C slip-resistant at ultimate	$F_{v,Ed} \leq F_{s,Rd}$ $F_{v,Ed} \leq F_{b,Rd}$ $F_{v,Ed} \leq N_{net,Rd}$	Preloaded 8.8 or 10.9 bolts should be used. For slip resistance at ultimate see 3.9. $N_{net,Rd}$ see 3.4.1(1) c).
Tension connections		
D non-preloaded	$F_{t,Ed} \leq F_{t,Rd}$ $F_{t,Ed} \leq B_{p,Rd}$	No preloading required. Bolt classes from 4.6 to 10.9 may be used. $B_{p,Rd}$ see Table 3.4.
E preloaded	$F_{t,Ed} \leq F_{t,Rd}$ $F_{t,Ed} \leq B_{p,Rd}$	Preloaded 8.8 or 10.9 bolts should be used. $B_{p,Rd}$ see Table 3.4.
The design tensile force $F_{t,Ed}$ should include any force due to prying action, see 3.11. Bolts subjected to both shear force and tensile force should also satisfy the criteria given in Table 3.4.		

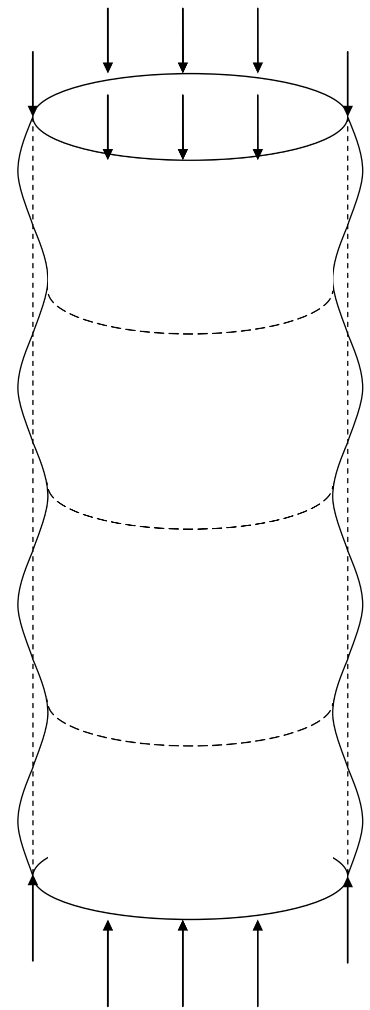
ULS: Buckling

For a **perfect** cylindrical shell under axial load,

$$\sigma_{cr} = 0.605\ E\ (t/R)$$

E = Modulus of elasticity,

t = Wall thickness, R = Shell radius



Imperfections

- are magnified by applied compression
- result in earlier onset of yield (on concave surfaces)

ULS: Buckling

Reference: **EC3-1-6**, sect 8 etc (tower)

Imperfections

First step: Decide the “fabrication tolerance quality class” – A, B or C

These correspond to % deviations of 0.6%, 1% and 1.6% respectively

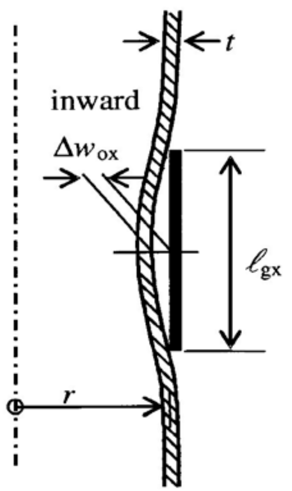
ULS: Buckling

The % imperfections of the finished tower section will be checked, using

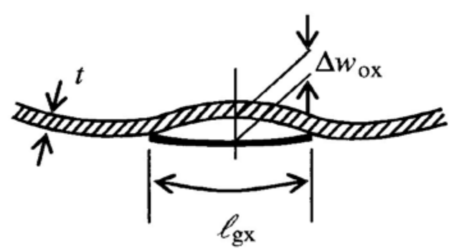
a) a straight rod of length L = $4(Rt)^{0.5}$ placed vertically anywhere

b) a curved gauge of same length placed circumferentially

c) a straight rod of length L = 25t placed vertically across horizontal welds

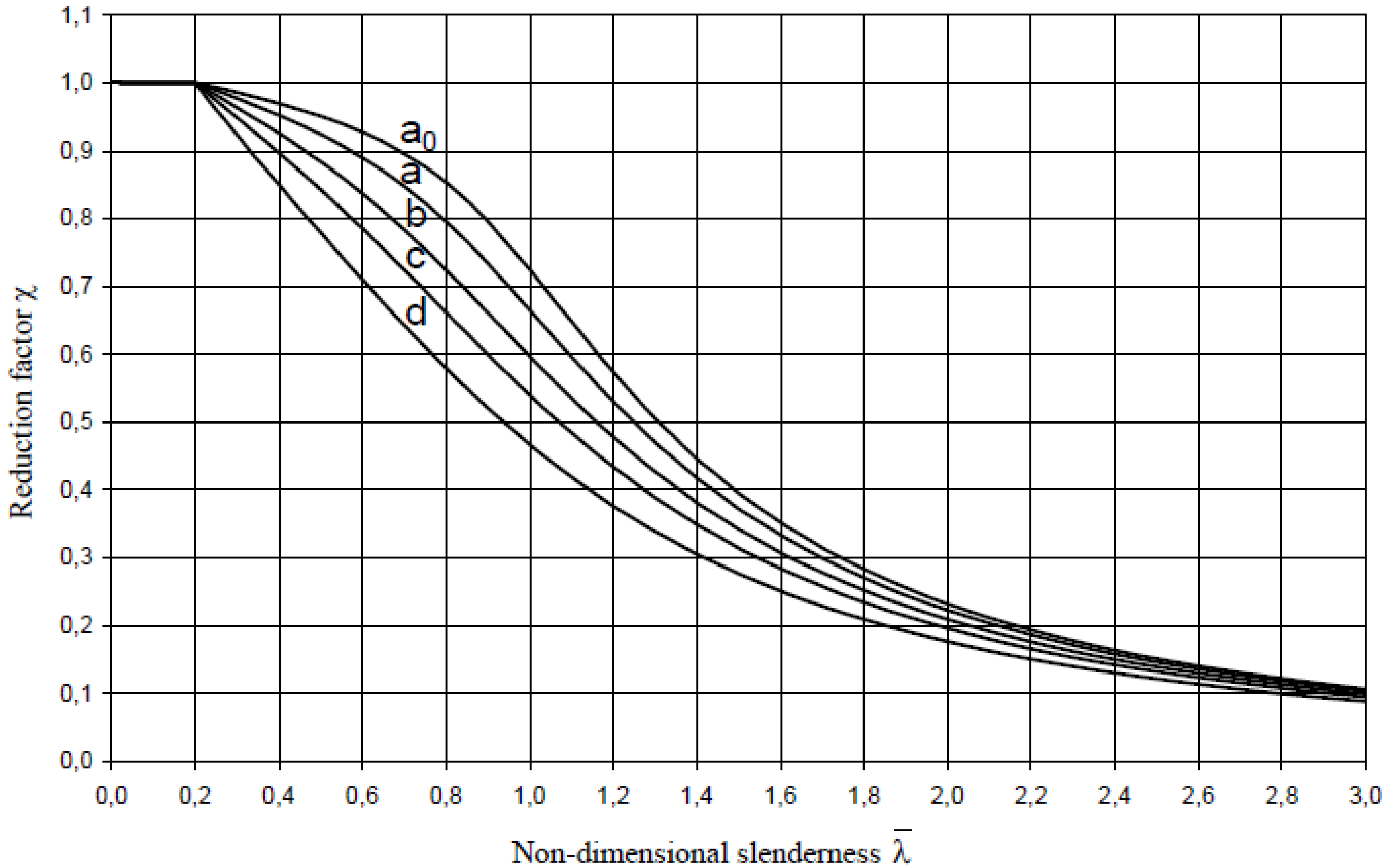


a) Measurement on a meridian (see 8.4.4(2)a)



b) First measurement on a circumferential circle (see 8.4.4(2)a)

ULS: Buckling



Buckling curves (Euler hyperbola)

ULS: Buckling

The elastic critical buckling stress determines the relative shell slenderness, $\lambda = (f_y/\sigma_{cr})^{0.5}$

The buckling strength is then determined as a proportion of the yield strength, according to

- The relative shell slenderness, λ
- The fabrication tolerance quality class
- The balance of axial stresses and bending stresses

A low proportion of axial stress – as normally found on WTG towers – results in a relatively higher buckling strength.

ULS: Buckling

Resistance buckling stress

$$\sigma_{x,Rd} = \sigma_{x,Rk}/\gamma_{M1}, \quad \sigma_{\theta,Rd} = \sigma_{\theta,Rk}/\gamma_{M1}, \quad \tau_{x\theta,Rd} = \tau_{x\theta,Rk}/\gamma_{M1}$$

where

$$\sigma_{x,Rk} = \chi_x f_{yk}, \quad \sigma_{\theta,Rk} = \chi_\theta f_{yk}, \quad \tau_{x\theta,Rk} = \chi_\tau f_{yk} / \sqrt{3}$$

Buckling reduction factor
(slenderness, imperfections, …)

Checks

$$\boxed{\sigma_{x,Ed} \le \sigma_{x,Rd}, \qquad \sigma_{\theta,Ed} \le \sigma_{\theta,Rd}, \qquad \tau_{x\theta,Ed} \le \tau_{x\theta,Rd}}$$

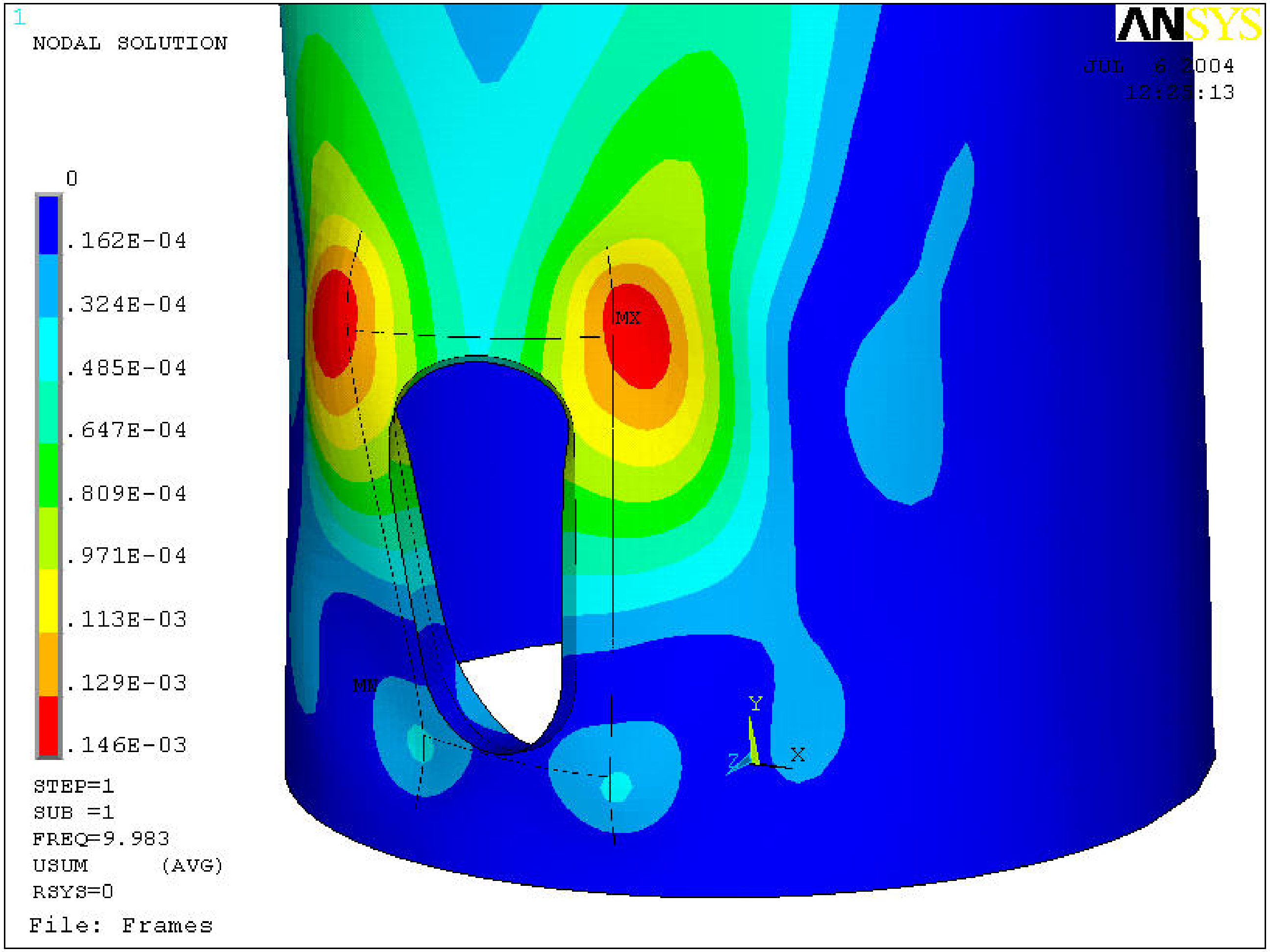
+ combined loading check

ULS: Buckling

Tower doorways

Tower doorways are always stiffened round the edge, but standard rules for a cylindrical shell no longer apply. FE analysis can be used.

Analysis of buckling using finite elements



first buckling mode

ULS: Fatigue

A WTG tower may see 1,000,000,000 loading cycles in its life

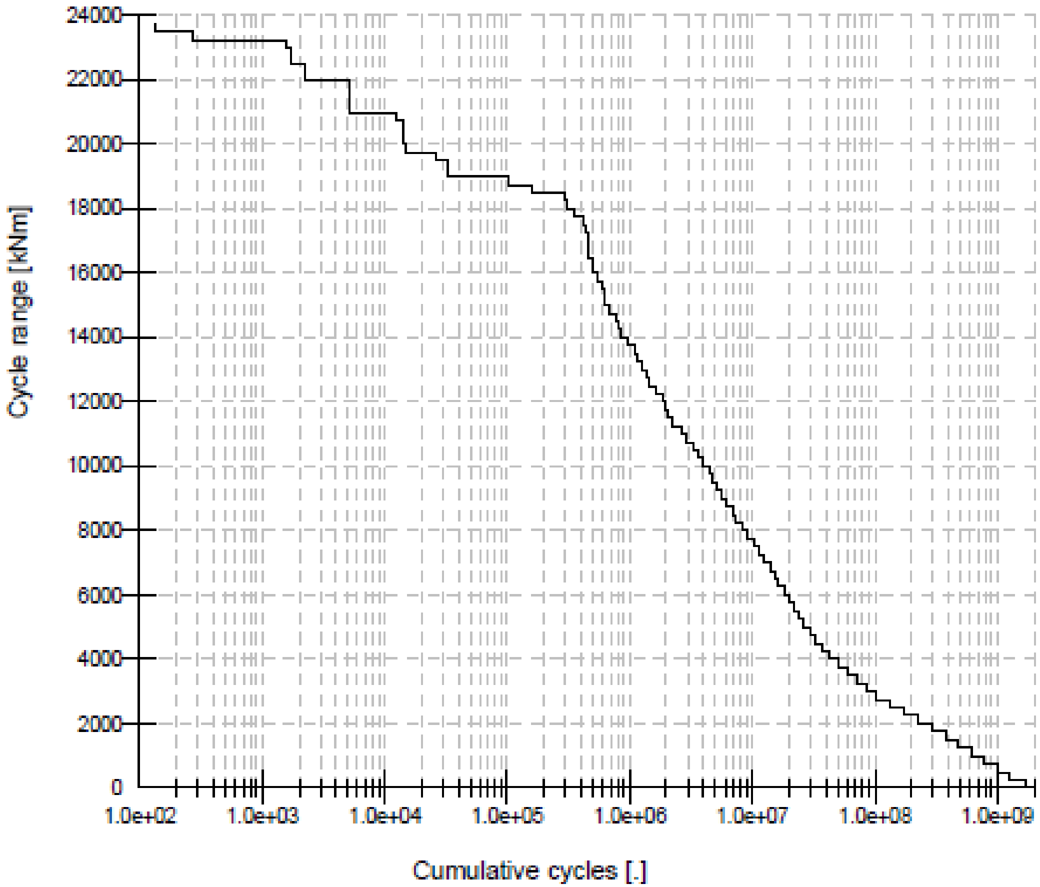
No. of load cycles = No. of blade passes
For 20 rpm 3 bladed machine operating continuously, this gives
20 x 3 x 60 x 8760 x25 = ca 800,000,000 cycles

The turbine manufacturer describes these loads in terms of **fatigue load spectra**.

These are tables of load ranges (eg tower base bending moment or TBOM) against numbers of cycles.

ULS: Fatigue

Example of fatigue load spectrum



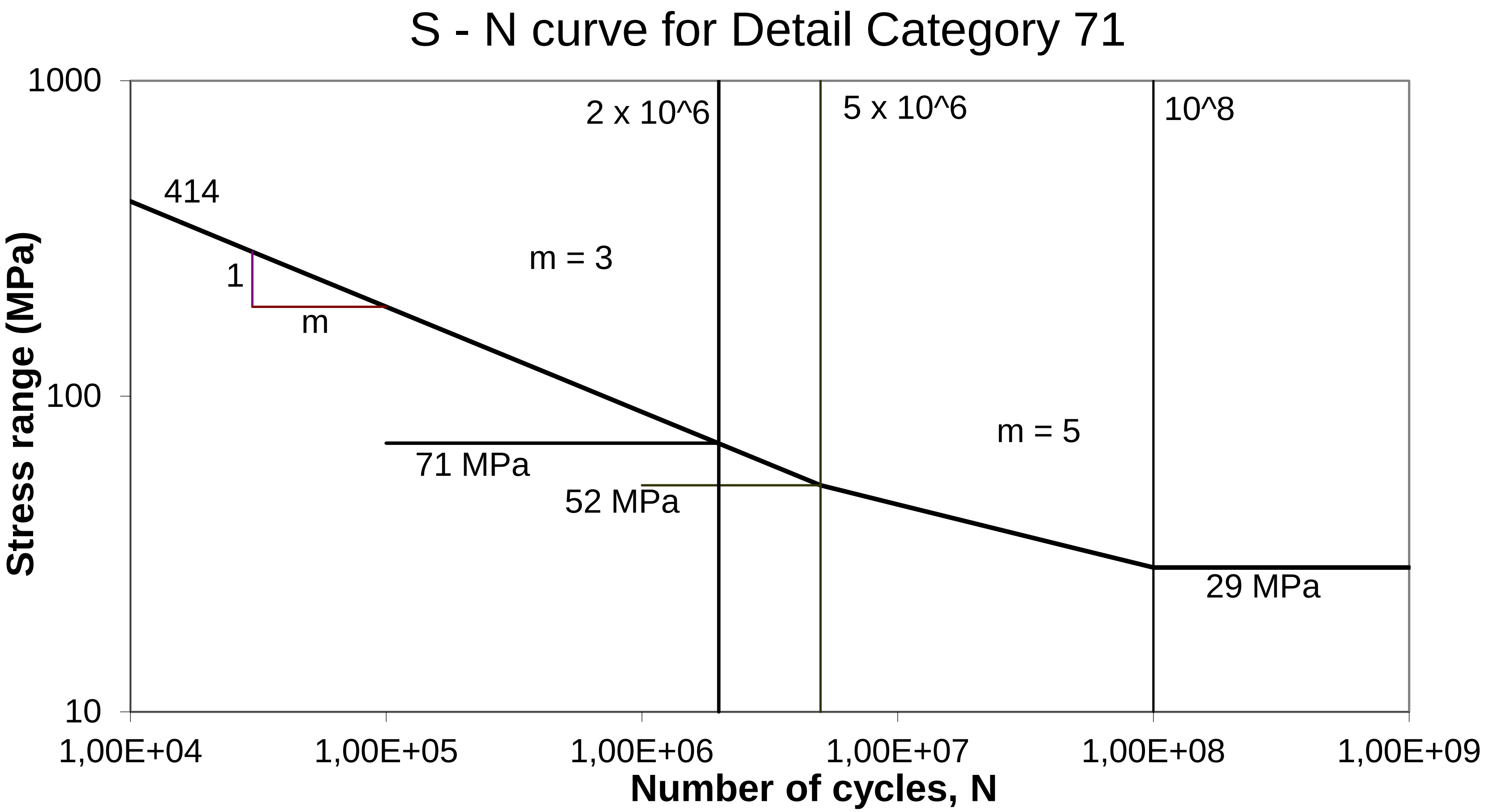
ULS: Fatigue

Fatigue bending moment ranges are converted to stress ranges using $\sigma = M/Z$.

[Load safety factor = Material safety factor = 1.0]

S/N curves give the number of constant amplitude load cycles permitted for each stress range.

ULS: Fatigue


S - N curve for Detail Category 71
Stress range (MPa)
1000
100
10
2 x 10^6
5 x 10^6
10^8
414
1
m
m = 3
m = 5
71 MPa
52 MPa
29 MPa
1,00E+04
1,00E+05
1,00E+06
1,00E+07
1,00E+08
1,00E+09
Number of cycles, N

ULS: Fatigue

Combining stress ranges of different sizes

Use Miner's rule.
For *j* different stress ranges:

Fatigue Damage Sum = $\frac{n_1}{N_1} + \frac{n_2}{N_2} + \frac{n_3}{N_3} + \cdots \frac{n_j}{N_j} < 1$

where n_1, n_2 etc are actual numbers of cycles in each stress range
& N_1, N_2 etc are permitted number of cycles for each stress range

Fatigue Detail Classification – Weld Seams

Table 8.2 EC3-1-9

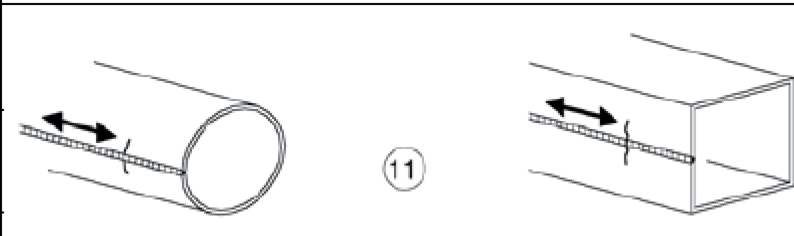
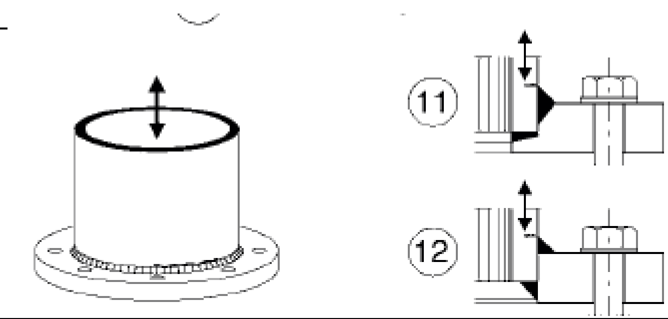
140		11) Automatic longitudinal seam weld without stop/start positions in hollow sections	11) Free from defects outside the tolerances of EN 1090. Wall thickness t ≤ 12,5 mm.
125		11) Automatic longitudinal seam weld without stop/start positions in hollow sections	11) Wall thickness t > 12,5 mm.
90		11) with stop/start positions	
For details 1 to 11 made with fully mechanized welding the categories for automatic welding apply.			

Table 8.5 EC3-1-9

71		11) Tube socket joint with 80% full penetration butt welds.	11) Weld toe ground. $\Delta\sigma$ computed in tube.
40		12) Tube socket joint with fillet welds.	12) $\Delta\sigma$ computed in tube.

ULS: Fatigue

Bolted flange joints

Bolts are preloaded –
Results in big reduction in stress range. However, fatigue of bolts still needs to be checked.

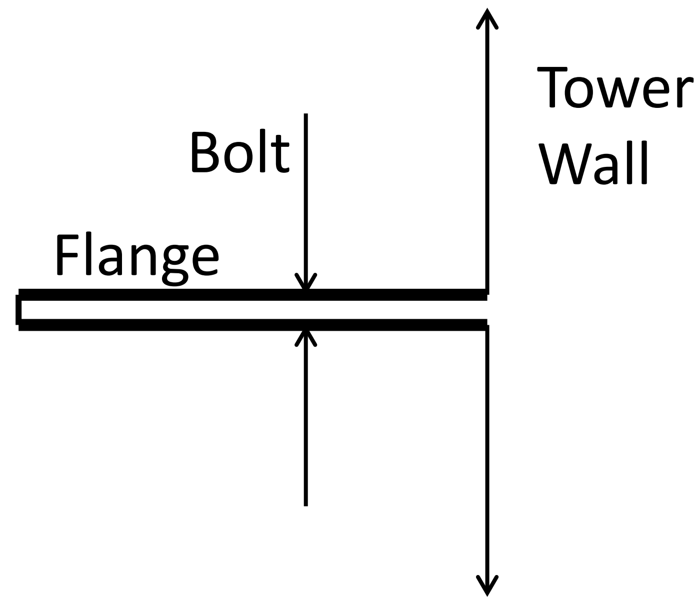
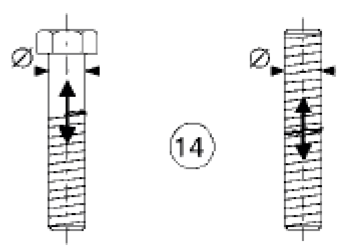


Table 8.1 EC3-1-9

50	size effect for $t > 30\text{mm}$: $k_s=(30/t)^{0.25}$		14) Bolts and rods with rolled or cut threads in tension. For large diameters (anchor bolts) the size effect has to be taken into account with k_s.	14) $\Delta\sigma$ to be calculated using the tensile stress area of the bolt. Bending and tension resulting from prying effects and bending stresses from other sources must be taken into account. For preloaded bolts, the reduction of the stress range may be taken into account.

Serviceability LS: joints

Reference: **EC3-1-6**, sect 8 etc (bolted joints)

Table 3.2: Categories of bolted connections

Category	Criteria	Remarks
Shear connections		
A bearing type	$F_{v,Ed} \leq F_{v,Rd}$ $F_{v,Ed} \leq F_{b,Rd}$	No preloading required. Bolt classes from 4.6 to 10.9 may be used.
B slip-resistant at serviceability	$F_{v,Ed.ser} \leq F_{s,Rd,ser}$ $F_{v,Ed} \leq F_{v,Rd}$ $F_{v,Ed} \leq F_{b,Rd}$	Preloaded 8.8 or 10.9 bolts should be used. For slip resistance at serviceability see 3.9.
C slip-resistant at ultimate	$F_{v,Ed} \leq F_{s,Rd}$ $F_{v,Ed} \leq F_{b,Rd}$ $F_{v,Ed} \leq N_{net,Rd}$	Preloaded 8.8 or 10.9 bolts should be used. For slip resistance at ultimate see 3.9. $N_{net,Rd}$ see 3.4.1(1) c).

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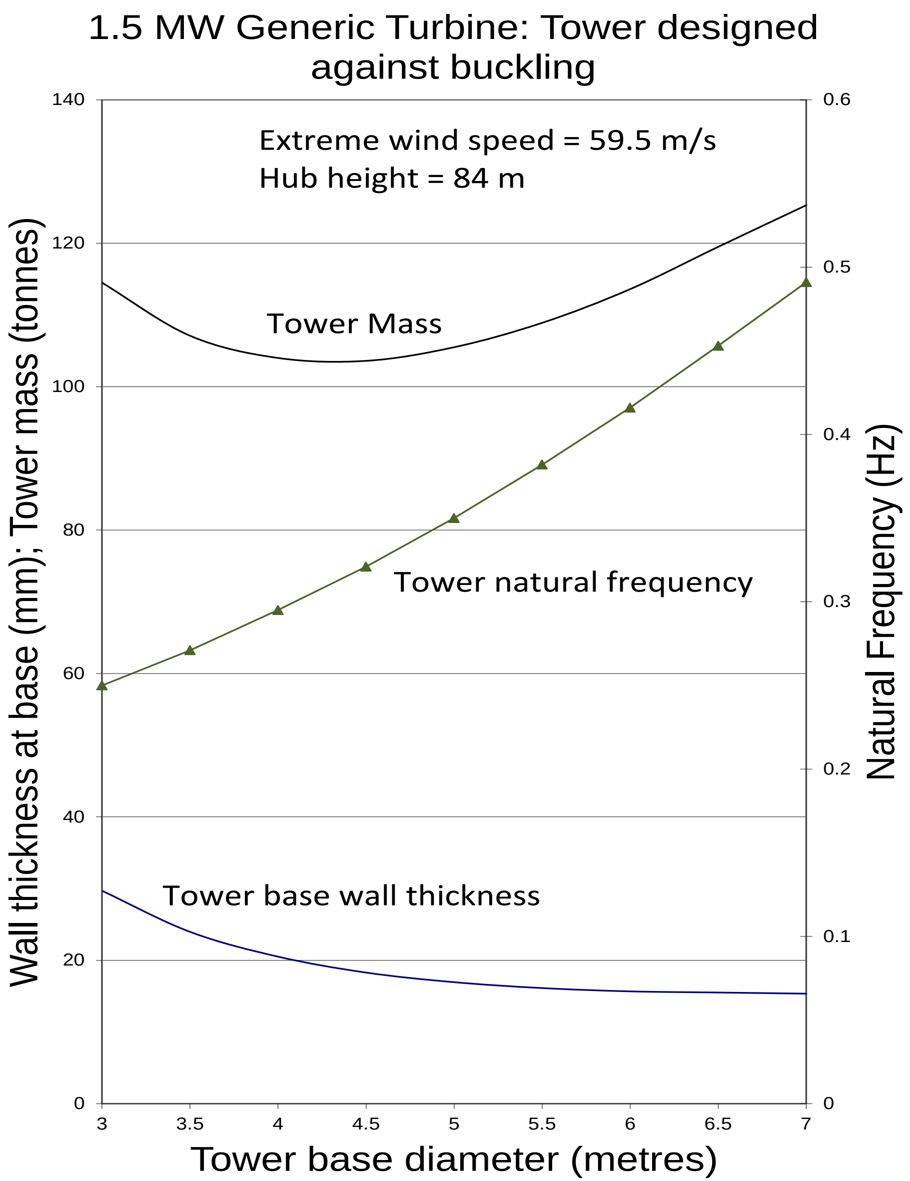
Avoidance of resonance



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Avoidance of resonance

Sources of Tower Excitation

A. Blade passing frequency

Stochastic wind loading (gust slicing)
Each blade "slices through" a localised gust in turn. Dominant effect.

Tower shadow
Load on each blade drops off sharply as it passes behind tower

Wind shear, yaw, shaft tilt
Largely averaged out over three blades – 2^{nd} order

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Avoidance of resonance

Sources of Tower Excitation

B. Rotational frequency

Blade pitch error

+/- 0.3 degrees specified in 2003 GL rules
=> thrust variation of ~+/- 1% of steady thrust

Rotor mass imbalance

0.005R eccentricity specified in 1999 GL rules
=> moment variation of ~+/-1% of max thrust x R

Avoidance of resonance

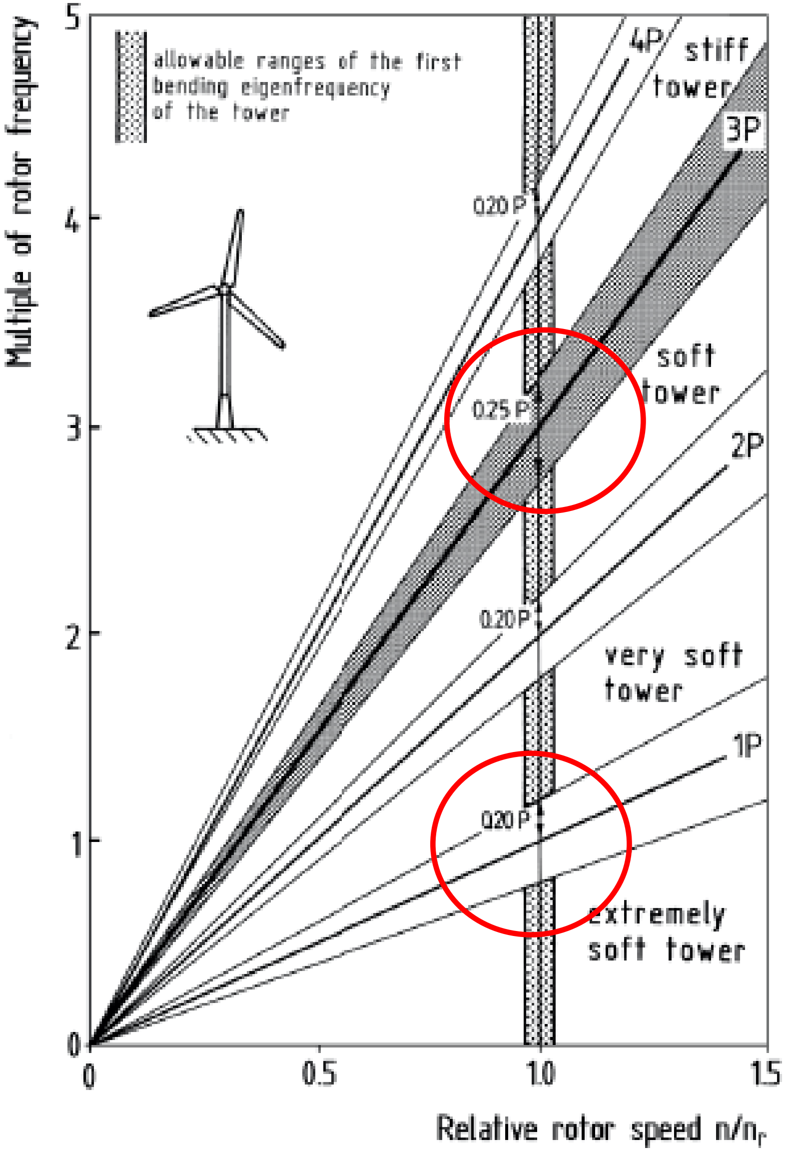

Fig. 7.20. Tower stiffness in the resonance diagram of a wind turbine with a three-bladed rotor

Hau (2006)

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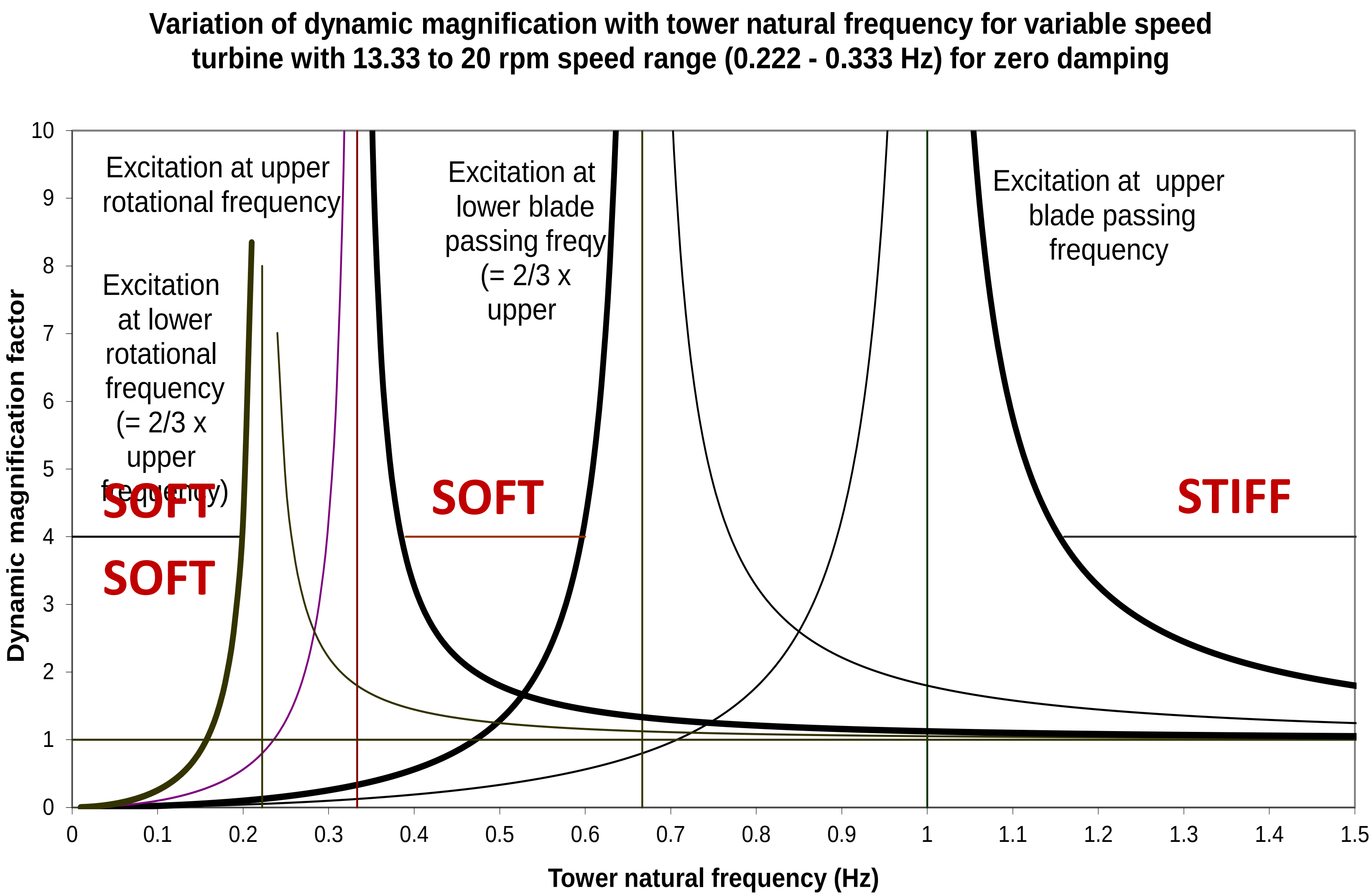
Avoidance of resonance



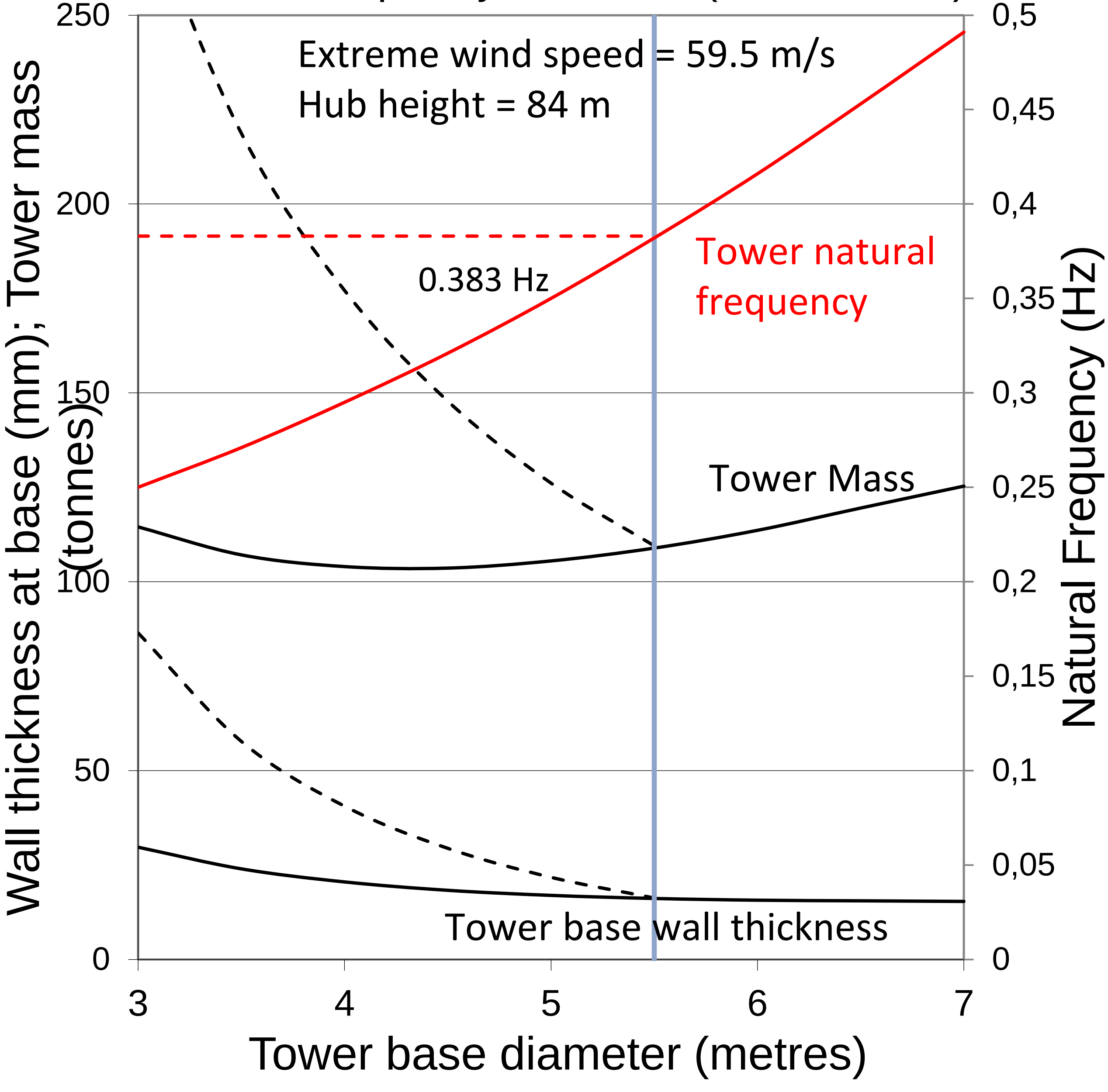
Avoidance of resonance

Design options

Second moment of area ($\pi R^3 t$) restricted by natural frequency limitations.

Initially, increasing the R/t ratio gives more efficient use of material, but at high R/t the buckling reduction factor penalty increases.

1.5 MW Generic Turbine: Applicn of 0.383 Hz minimum frequency constraint (dashed lines)



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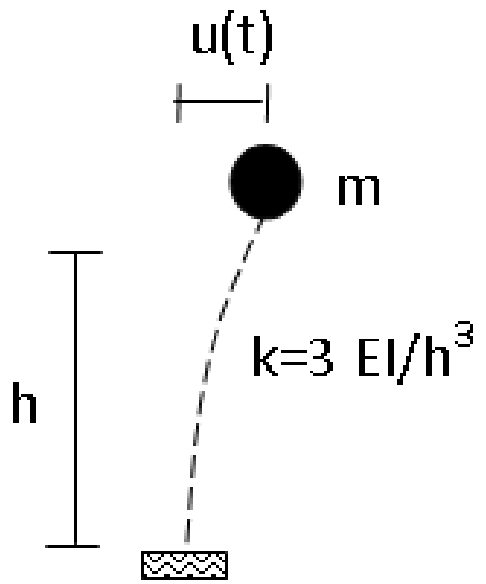
Avoidance of resonance

An estimate of the natural frequency

A wind turbine and its tower can be idealised as a mass on a weightless, uniform cantilever.



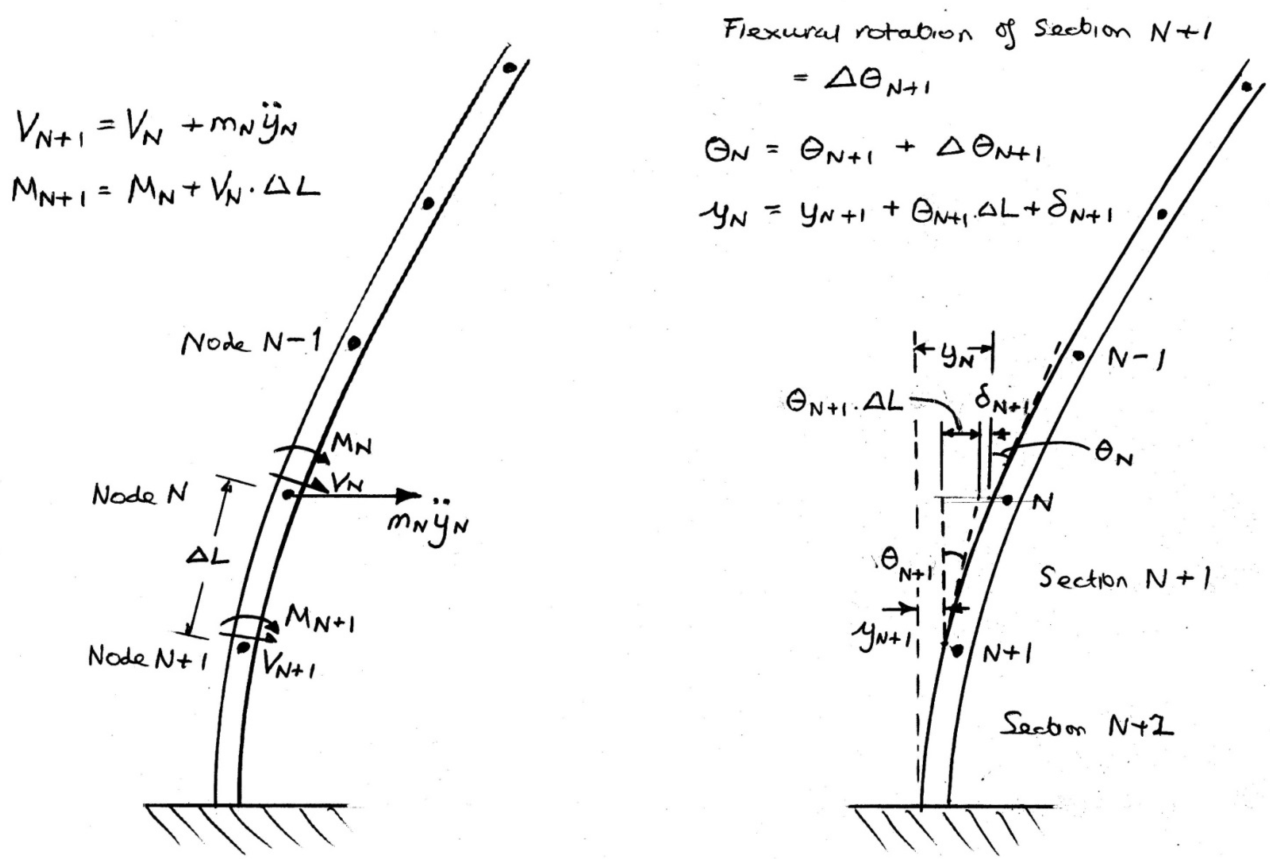
Equation of motion (free vibr)

$\ddot{u}(t)+ \omega^2 u(t)=0$, $\omega=\sqrt{k/m}$

ω: radian frequency

T: period $T=2\pi/\omega$

Stodola method for the comput. of the nat freq



TOWER NATURAL FREQUENCY SPREADSHEET NOTATION

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Stodola method for the comput. of the nat freq

SPREADSHEET TO CALCULATE NATURAL FREQUENCY USING STODOLA METHOD

TOWER NATURAL FREQUENCY : FIRST MODE										E KN/m2	2.10E+08										
													First mode freqy		0.43431	Hz	Last itern				
Hub height, H	84	m				Tower head mass (excluding rc				84854	kg		First mode freqy		0.4343	Hz	Penultimate iteration				
Tower top OD	2.82	m				Hub inertia				3.36E+06	kg.m^2										
			Outside	Mean	Mean					Density	7.43	T/cum		Mean							
	Height	Sectn	Dia	Dia	Dia									2nd Mom	Inboard	Inboard		Node	Normal		Mass
	at node	Wall	at	at	at	Mass	Discret	Total	Node	Trial	Inertia Fce	Shear Fce	Moment	of Area	Element	Element	total	total	-ised		per unit
Bay	(top of	thick	top of	top of	sectn	at node	masses	mass	ht	deflectn	M.y	Inboard	at node	of inboard	deflectn	rotation	rotn	deflectic	Deflect		length
height	sectn)	ness	sectn	sectn	mid ht				h	(h/H)^2		of node		element	mm	mm/m		mm	-ion		kg/m
m	m	mm	m	m	m	kg					N	N	Nm	m^4							
	0			5.646																	
0	0	17.4	*5.663*	5.646		5783.4	0	5783	0	0	0	111144.6	8544713		0	0	0	0	0		2292.968
5.125	5.125	17.4	5.4855	5.468	5.557	11382	0	11382	5.125	0.003722	42.36892	111144.6	7975097	1.17245	0.44564	0.1719	0.1719	0.4456	0.0033		2220.876
5.125	10.25	17.4	5.308	5.291	5.379	10950	0	10950	10.25	0.01489	163.0493	111102.2	7405699	1.06365	0.45774	0.1765	0.3484	1.7845	0.0133		2148.784
5.125	15.375	17.2	5.1305	5.113	5.202	10521	0	10521	15.38	0.033502	352.4761	110939.1	6837136	0.95079	0.47463	0.1828	0.5312	4.0446	0.03		2052.903
5.125	20.5	17.2	4.953	4.936	5.025	9953.3	0	9953	20.5	0.059559	592.8112	110586.7	6270379	0.8568	0.48525	0.1867	0.7178	7.2521	0.0539		1981.64
5.125	25.625	16.5	4.7755	4.759	4.847	9393.3	0	9393	25.63	0.093061	874.1489	109993.9	5706660	0.73802	0.5154	0.198	0.9159	11.446	0.085		1832.898
5.125	30.75	16.5	4.598	4.582	4.67	8855.5	0	8855	30.75	0.134008	1186.705	109119.7	5147422	0.66003	0.52304	0.2007	1.1165	16.663	0.1238		1764.535
5.125	35.875	15.8	4.4205	4.405	4.493	8325.1	0	8325	35.88	0.1824	1518.497	107933	4594265	0.5628	0.55148	0.2112	1.3278	22.937	0.1704		1624.472
5.125	41	15.8	4.243	4.227	4.316	7792.2	0	7792	41	0.238237	1856.402	106414.5	4048891	0.49882	0.55319	0.2114	1.5392	30.295	0.2251		1559.009
5.125	46.125	15	4.0655	4.051	4.139	7267.9	0	7268	46.13	0.301519	2191.418	104558.1	3513031	0.41763	0.57955	0.2209	1.7601	38.763	0.288		1418.204
5.125	51.25	15	3.888	3.873	3.962	6791.6	0	6792	51.25	0.372245	2528.155	102366.7	2988402	0.36628	0.56994	0.2166	1.9767	48.354	0.3592		1356.055
5.125	56.375	14.3	3.7105	3.696	3.785	6322.7	0	6323	56.38	0.450417	2847.856	99838.53	2476729	0.30441	0.57889	0.2191	2.1958	59.063	0.4388		1233.759
5.125	61.5	14.3	3.533	3.519	3.607	5589.3	0	5589	61.5	0.536033	2996.05	96990.67	1979652	0.26363	0.54821	0.2063	2.4021	70.865	0.5265		1174.511
5.125	66.625	12.2	3.3555	3.343	3.431	4878.6	0	4879	66.63	0.629094	3069.131	93994.62	1497929	0.1935	0.58791	0.2193	2.6214	83.763	0.6223		952.0809
5.125	71.75	12.2	3.178	3.166	3.255	3977.1	0	3977	71.75	0.729601	2901.691	90925.49	1031936	0.16516	0.50838	0.1869	2.8083	97.706	0.7259		901.5338
5.125	76.875	8.7	3.0005	2.992	3.079	3112.8	0	3113	76.88	0.837552	2607.168	88023.8	580814	0.09971	0.55293	0.1974	3.0057	112.65	0.8369		607.5619
5.125	82	8.7	2.823	2.814	2.903	1510.7	0	1511	82	0.952948	1439.612	85416.63	143054	0.08359	0.32537	0.1057	3.1113	128.38	0.9538		571.5159
1.3	83.3	0	0	0	0	0	52839	52839	83.3	0.983403	51962.02	83977.02	0	100	2.9E-06	3E-06	3.1113	132.43	0.9838		
0.7	84	0	0	0	0	0	32015	32015	84	1	32015	32015	79024.1	*100*	1.2E-05	1E-05	3.1113	134.6	1		
					Sum	122407	84854	2E+05	slope	0.023526	3359000	Hub mom	79024.1		Nat frequency		0.4338	Hz			

Stodola method for the comput. of the nat freq

TOWER NATURAL FREQUENCY SPREADSHEET - CALCULATION STEPS 1 - 5

1. Divide tower into sections (not necessarily of equal length) Column A and calculate heights of nodes at top of each sections. Number the nodes from top to bottom, starting with the notional node at hub level
Column B

2. Enter section wall thicknesses, t Column C

3. Enter outside diameter at top of each section (can calculate by interpolation if tower is uniformly tapered), D_o Column D

4. Calculate tower mean diameter at top of each section (= D_o – t)
Column E

and then tower mean diameter at mid-height of each section Column F

5. Calculate section masses and allocate half to node above
nd half to node below Column G

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Stodola method for the comput. of the nat freq

TOWER NATURAL FREQUENCY SPREADSHEET - CALCULATION STEPS 6 - 12

6. Insert nacelle and rotor masses and any tower discrete masses (eg masses of intermediate flanged joints, if known) Column H

7. Calculate total mass at each node Column I

8. Calculate parabolic trial deflected profile $y_N = y_T(h_N/H)^2$ Column K

9. Assume tower is oscillating from side to side with the mode shape defined by the parabolic trial deflected profile. Assume that the maximum acceleration at hub height is 1 m/s^2. Then the maximum accelerations at other nodes are given by $y_N'' = (h_N/H)^2$ m/s^2.

10. Calculate inertia loading at each node, $m_N y_N''$. Column L

11. Calculate shear force below each node, $V_{N+1} = V_N + m_N y_N'$ and the moment at each node, $M_{N+1} = M_N + V_N DL$ Columns M & N

12. Calculate 2nd moment of area at mid-height of each section, $I_N = p(D_N/2)^3.t_N$ (Treat the section(s) between the tower top and hub level as effectively rigid and assign a very large value to the 2nd moment(s) of area) Column O

Stodola method for the comput. of the nat freq

TOWER NATURAL FREQUENCY SPREADSHEET - CALCULATION STEPS 13 - 18

13. Calculate flexural deflection over length of each section (inboard of node)

$d_N = V_N DL^3/3EI_N + M_N DL^2/2EI_N$ Column P

14. Calculate flexural rotation over length of each section (inboard of node)

$Dq_N = V_N DL^2/2EI_N + M_N DL/EI_N$ Column Q

15. Calculate total rotation at each node $q_N = q_{N+1} + Dq_{N+1}$ Column R

and the total deflection at each node $y_N = y_{N+1} + q_{N+1}DL + d_{N+1}$ Column S

16. Noting that the hub height acceleration of 1 m/s^2 equates to w^2y_T, calculate natural frequency as $f = (1/2\pi)/y_T^{0.5}$ Hz.

17. Calculate the normalised deflected profile or mode shape, y_N/y_T.

Column T

18. Repeat whole calculation using new deflected profile calculated in (17) Instead of the parabolic trial deflection used the first time.

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Blade Clearance

Blades bending close to tower

Image: Vestas

Transportation

Heights of overbridges limit tower diameters to about 4 metres.

Limitation in length and in weight (UK Govt transportation rules).