Small Wind Turbines: Analysis, Design and Application

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In 1924 Russell Grimwade installed a small wind turbine on his farm near Frankston, Victoria, Australia

"The electric mains are nowhere within reach. Artificial illumination must be provided and here we displayed our eccentricities to the full. A windmill was set up on an attractive hardwood tower that housed the batteries in its base. For artistic effect it gained full marks – for the effective generation of electricity it hardly scored a point. … It was bad engineering that the mill should fail to come up to the wind so that it ran backwards until something broke. …I still believe that man [sic] will someday make use of the power of the wind for his own purpose, and I feel that I have contributed to that research by demonstrating that my method was not the way to do it."

Can we do better 80 years later?

Ch	Title	Programs
1	Introduction to Wind Turbine Technology	Ground level noise propagation
2	Control Volume Analysis for Steady Flow	
3	Blade Element Theory	Basic blade (BE) element analysis
4	Aerofoils: Lift, drag, and Circulation	
5	The Steady Aerodynamics of Power Extraction	Full BE analysis for power production
6	The Quasi-steady Aerodynamics of Starting and Low Wind Speed Performance	BE analysis for starting
7	Blade Design, Manufacture, and Testing	Numerical multi-dimensional optimization of blade design
8	The Unsteady Aerodynamics of Turbine Yaw and Over-speed Protection	
9	Design Requirements of the IEC Simple Load Model	Spreadsheet for IEC simple load model
10	Tower Design and Manufacture	Monopole tower design, multi-dimensional optimization
11	Control System, Battery Charging, and Grid Connection	Co-authored by Peter Freere and Ed Nowicki
12	Site Assessment and Installation	

Chapter 1

Parameter	Power law dependence on blade radius, *R*
Blade angular velocity	-1
Centrifugal blade loads	-1
Reynolds number	1
Gearbox ratio	1
Power output	2
Noise output	2
Brake torque (high speed side)	2
Brake torque (low speed side)	3
Aerodynamic starting torque	3
Blade mass	2 - 3
Gyroscopic moments	3 - 4
Inertia of blades	4 - 5

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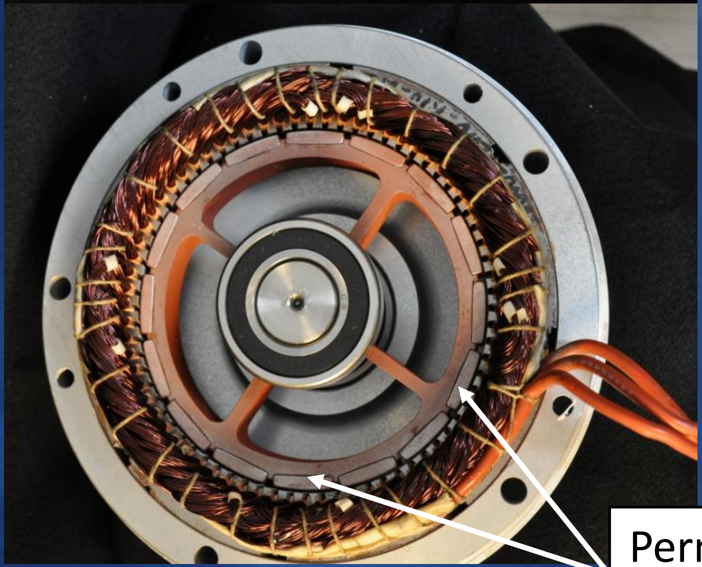
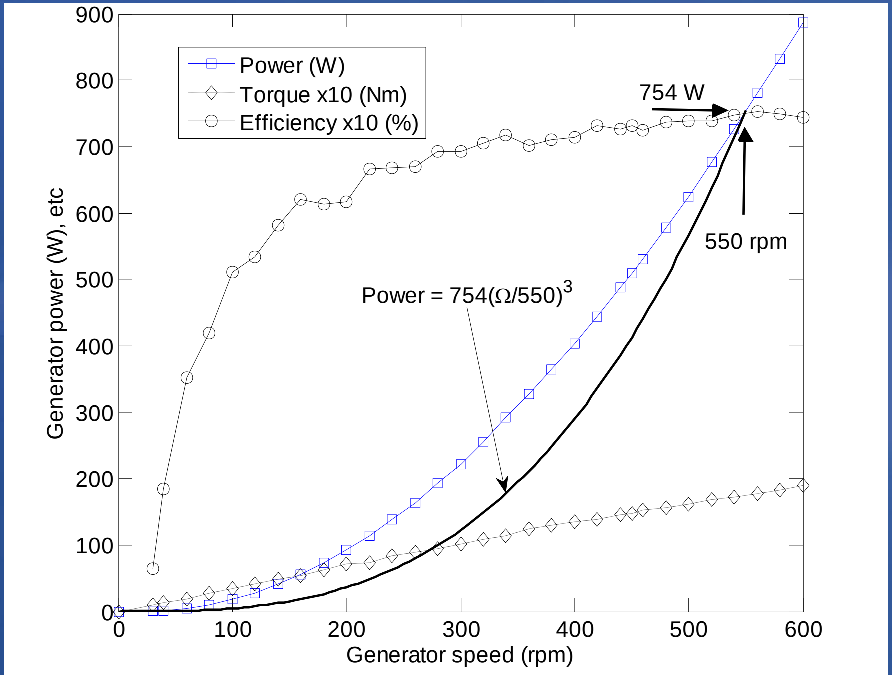
Chapter 7
Design Example





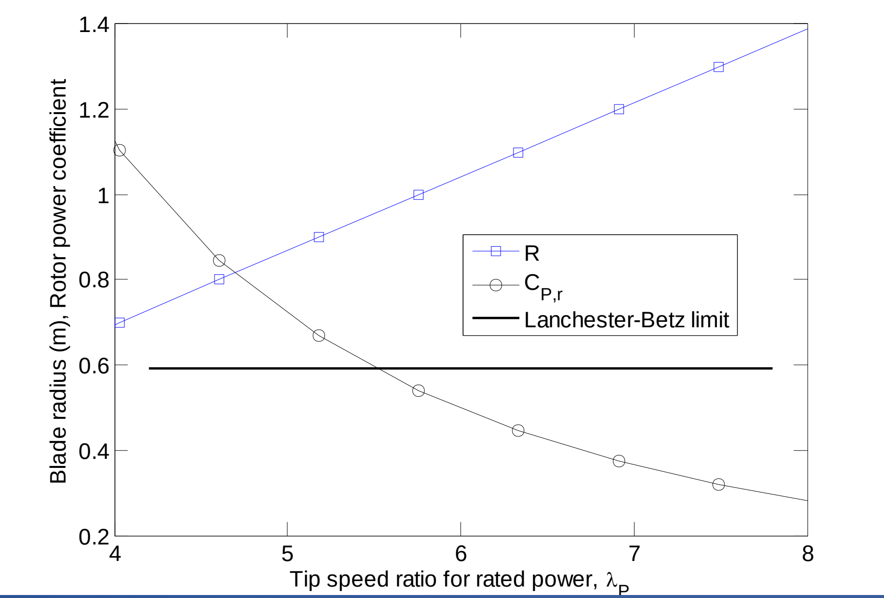
Permanent magnets

Design Example

No. blades = 3   Resistive torque = 0.5 Nm

$$C_{P,r} = \frac{754/0.74}{\frac{1}{2}\times 1.2\times 10^3 \times \pi R^2} = 0.541/R^2$$

$$\lambda_P = \frac{550\times 2\pi}{10\times 60} R = 5.759R$$



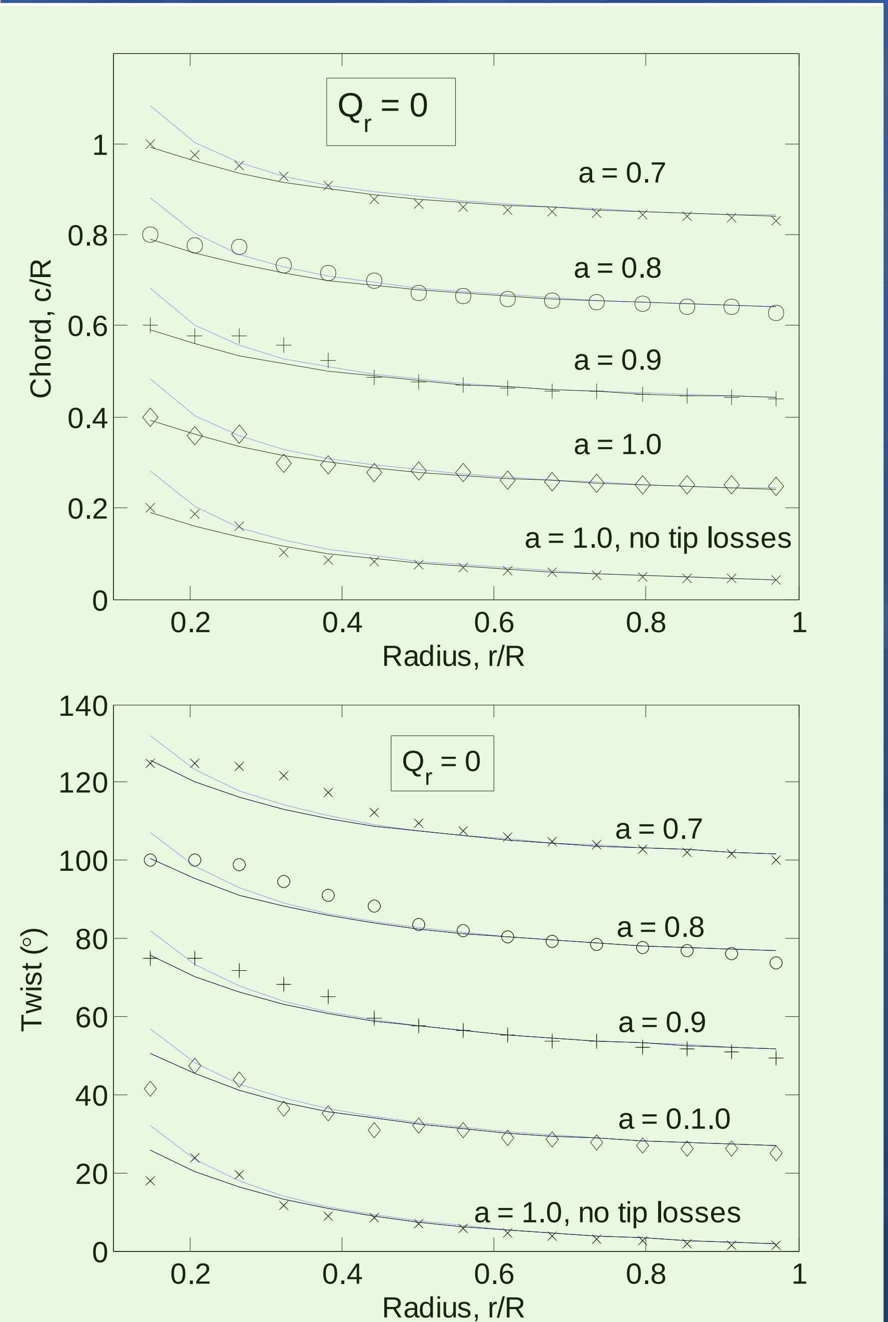
Use evolutionary optimization to optimization C_p and starting time T_s

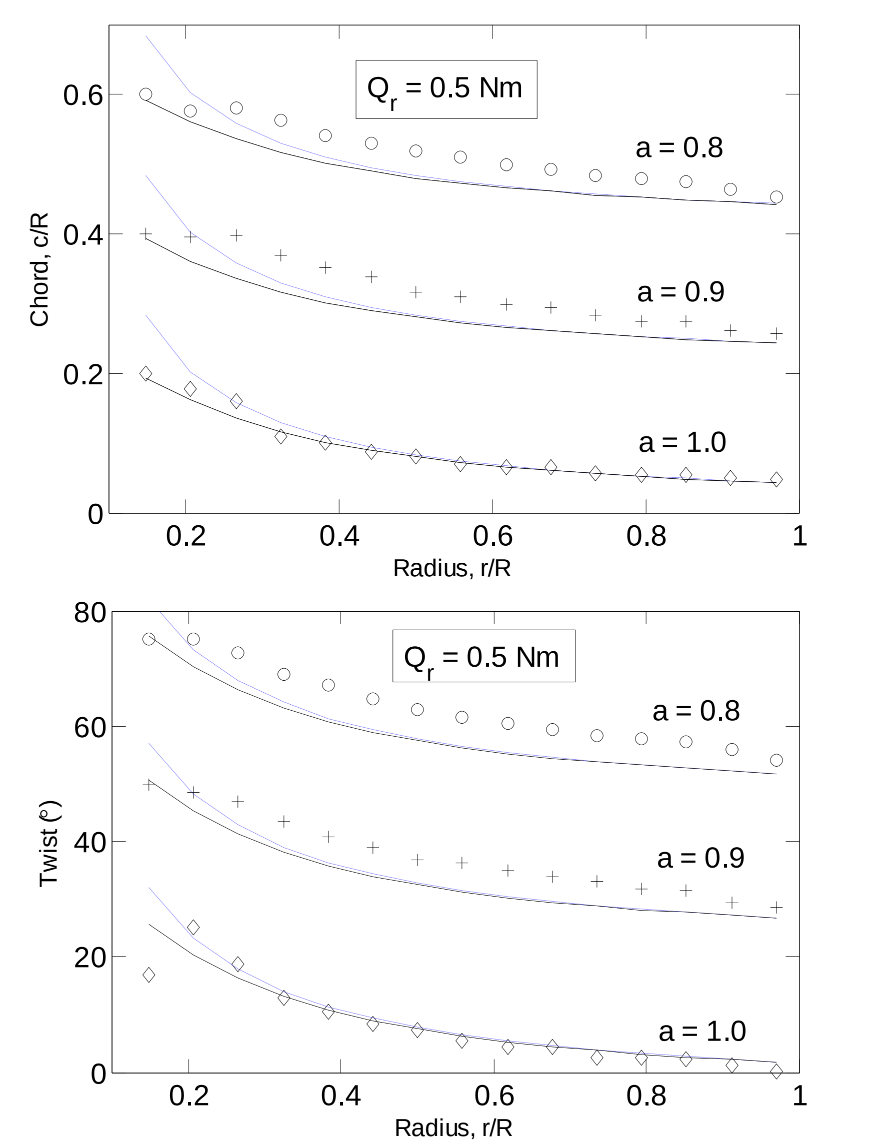
$$\text{fitness}(\mathbf{c}_i) = a\frac{C_p(\mathbf{c}_i)}{\max(C_p)} + (1-a)\frac{\min(T_s)}{T_s(\mathbf{c}_i)}$$

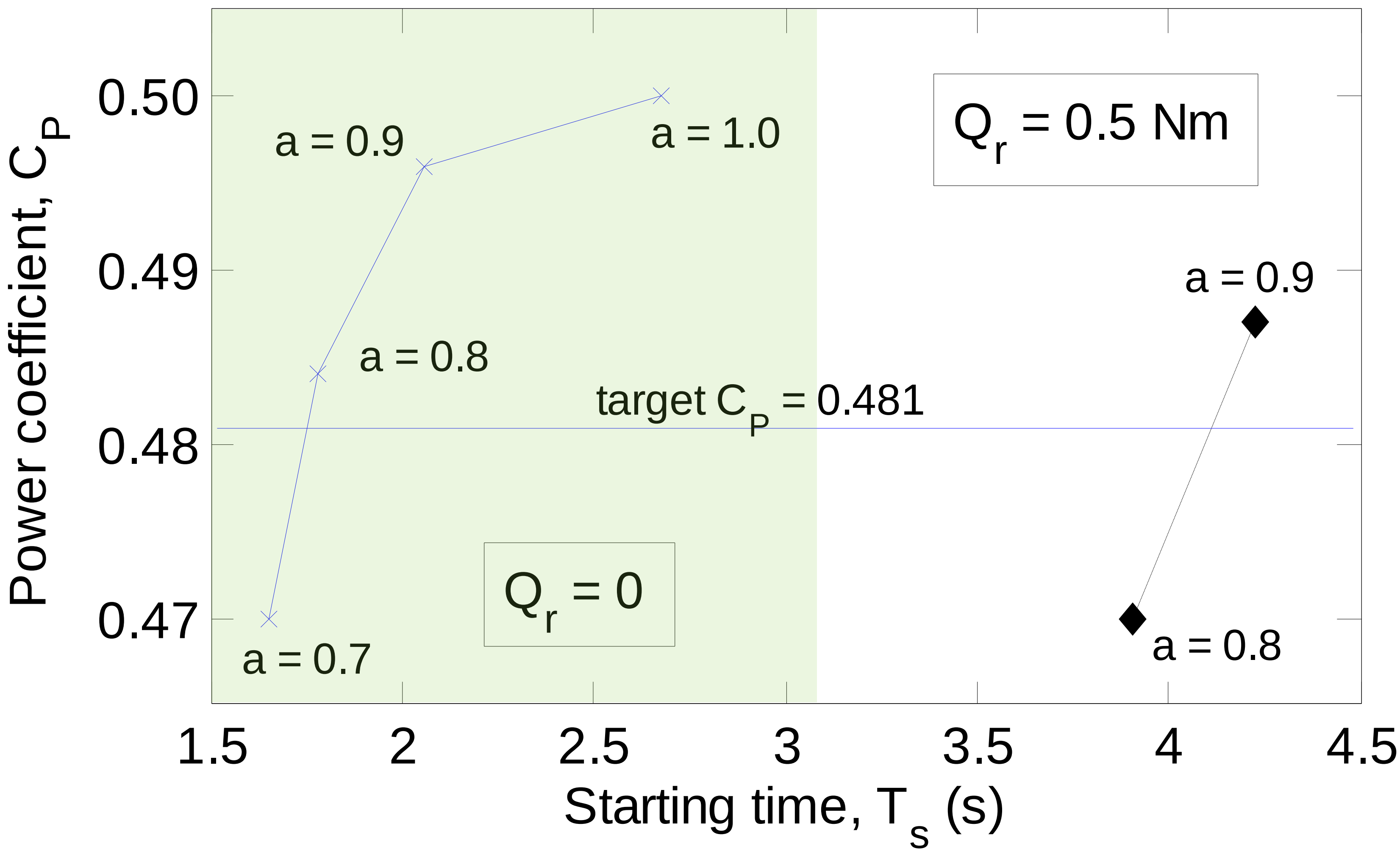
Choose $C_{P,r}$ = 0.481

Parameter & value	Parameter & value
N = 3	ρ_b = 550 kgm^{-3}
U_s = 5 m/s	U_p = 10 m/s
λ_f = 1.0	λ_p = 6.10
R = 1.06 m	Aerofoil section SG 6043
Maximum chord, c/R = 0.2	Minimum c/R = 0.01
Maximum twist= 25°	Minimum twist = -5°
Maximum power = 754 W	**Resistive torque = 0 and 0.5 Nm**
Generator inertia = 0.006 kgm^2	**r_h = 0.125**

Successive plots are displaced by 0.2 or 25°

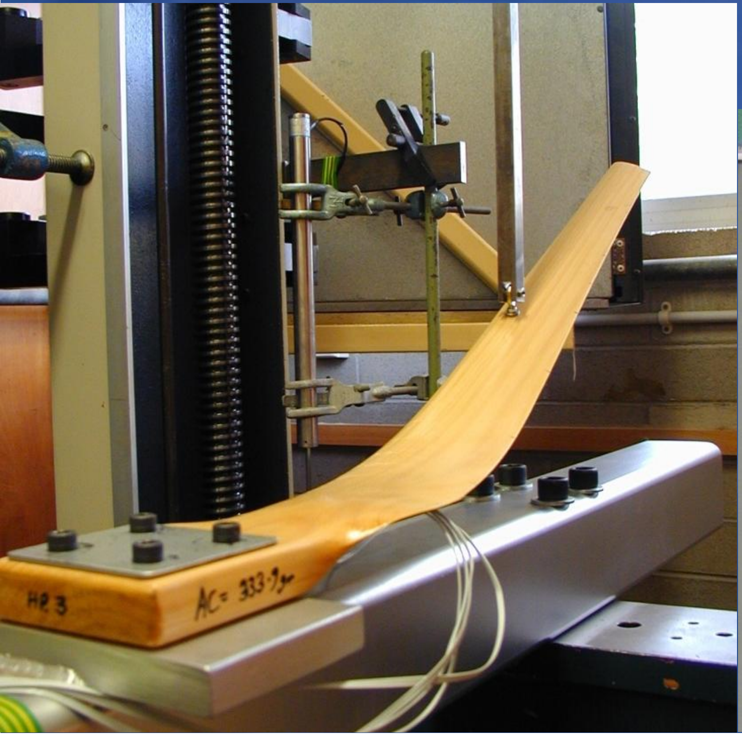


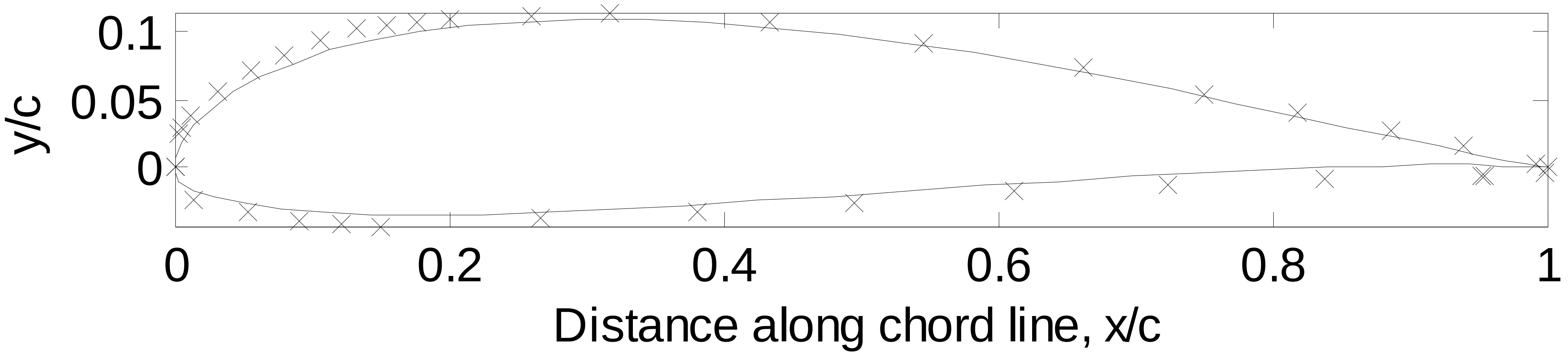




Power coefficient, C_P
Starting time, T_s (s)
0.50
0.49
0.48
0.47
1.5
2
2.5
3
3.5
4
4.5
a = 0.9
a = 1.0
a = 0.8
a = 0.7
target C_P = 0.481
Q_r = 0
Q_r = 0.5 Nm
a = 0.9
a = 0.8

Timber Blades 0.94 m long machined on a CNC miller





Timber Blades A cheaper way to make many blades accurately?

Photo from: www.radarcarve.com

Watch this space

Simple Load Model Results

Load Case A - Fatigue Loads on Blades and Rotor Shaft			
	Fatigue Damage Limit	**Fatigue Damage**	**Conclusion**
Blades	1.00	2.25E-06	SAFE
Shaft	1.00	Infinite Life	SAFE
Load Case B - Blade and Rotor Shaft Loads during Yaw			
	Material Stress Limit (MPa)	**Calculated Stress (MPa)**	**Conclusion**
Blades	13.33	0.27	SAFE
Shaft	27.78	40.29	FAIL
Load Case C - Yaw Error Load on Blades			
	Material Stress Limit (MPa)	**Calculated Stress (MPa)**	**Conclusion**
Blades	13.33	2.77	SAFE
Load Case D - Maximum Thrust on Shaft			
	Material Stress Limit (MPa)	**Calculated Stress (MPa)**	**Conclusion**
Shaft	13.33	0.65	SAFE
Load Case E - Maximum Rotational Speed			
	Material Stress Limit (MPa)	**Calculated Stress (MPa)**	**Conclusion**
Blades	13.33	4.25	SAFE
Shaft	27.78	1.14	SAFE
Load Case F - Short at Load Connection			
	Material Stress Limit (MPa)	**Calculated Stress (MPa)**	**Conclusion**
Blades	13.33	2.49	SAFE
Shaft	27.78	6.46	SAFE
Load Case G - Shutdown Braking			
	Material Stress Limit (MPa)	**Calculated Stress (MPa)**	**Conclusion**
Blades	13.33	n/a	n/a
Shaft	27.78	n/a	n/a
Load Case H - Parked Wind Loads during Idling			
	Material Stress Limit (MPa)	**Calculated Stress (MPa)**	**Conclusion**
Blades	13.33	3.58	SAFE
Shaft	27.78	1.86	SAFE

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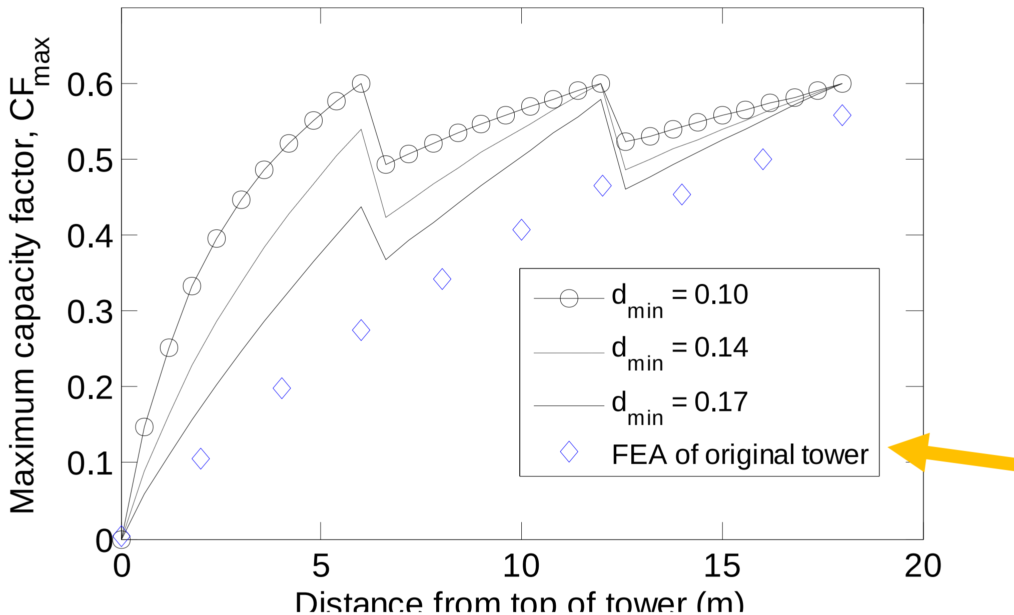
Chapter 9
IEC Simple Load Model assessment of 500 W turbine

Chapter 10 Tower Design: Optimization of an 18 m, 3-section octagonal tower for a 5 kW wind turbine



d_0 (m)	d_h (m)	t_1, t_2, t_3 (mm)	m_t (kg)
0.10	0.373	2.8, 3.6, 4.3	406.9
0.14	0.384	2.5, 3.4, 4.4	439.6
0.17	0.378	2.7, 3.5, 4.8	485.5
0.17	0.384	2.8, 3.6, 4.7	487.0
0.17	0.428	2.6, 3.4, 4.3	497.2
0.17	0.41	3.75, 3.75, 4.3	530.1

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CF = maximum stress/allowable stress

The Significance of Small Blades Having Very Low Inertia

Maximum power point tracking (MPPT) is normally based on *steady* power extraction but wind turbines live in an unsteady world

Can we exploit unsteady behaviour to improve energy capture?

How do we implement MPPT when generator and inverter efficiency decrease rapidly at part load?