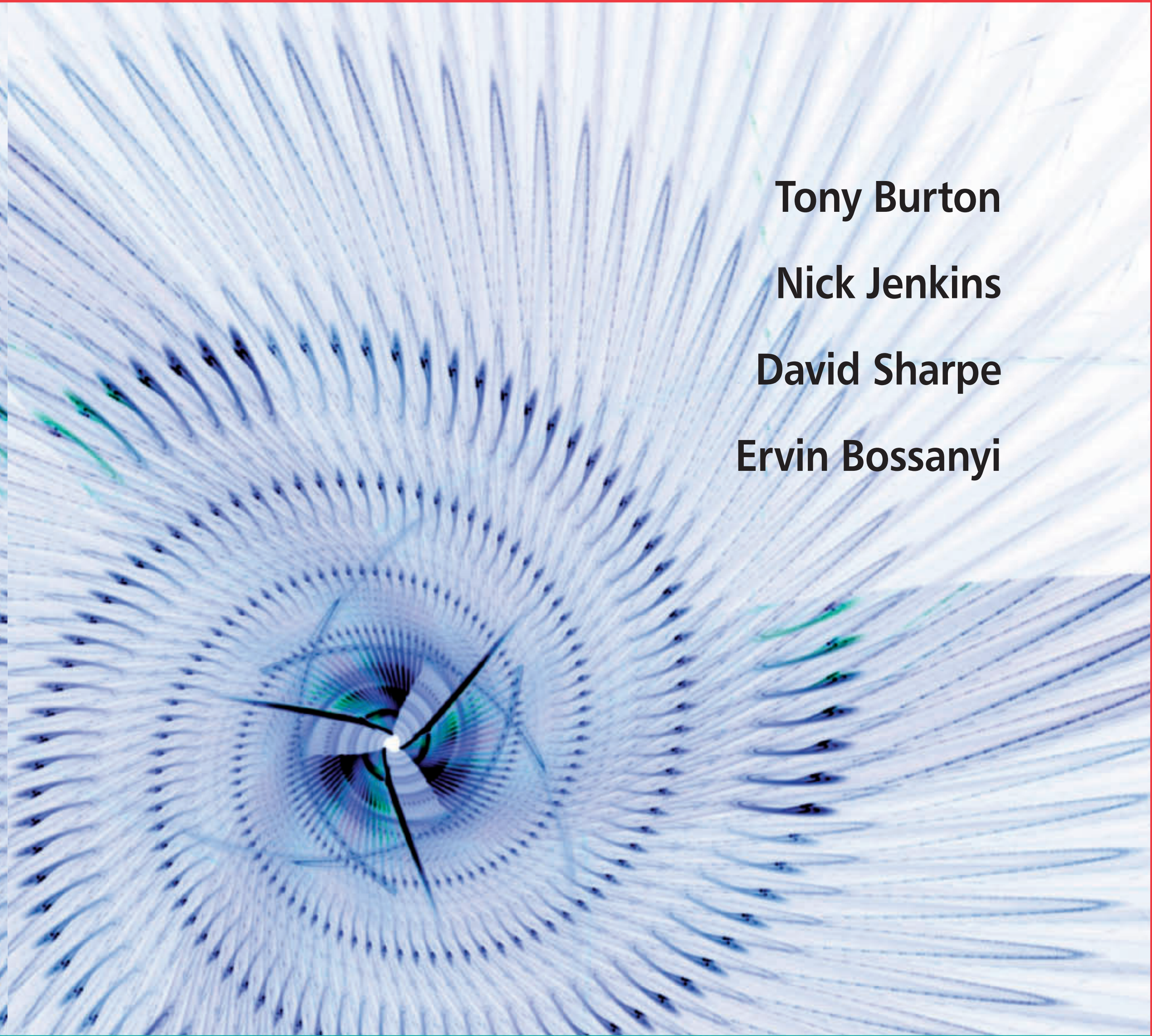

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Wind Energy Handbook

SECOND EDITION

WILEY

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Second Edition

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About the Authors

Tony Burton: After an early career in long-span bridge design and construction, Tony Burton joined the Wind Energy Group in 1982 to co-ordinate Phase IIB of the Offshore Wind Energy Assessment for the UK Department of Energy. This was a collaborative project involving British Aerospace, GEC and the CEGB, which had the task of producing an outline design and costing of a 100 m diameter wind turbine in a large offshore array. Following this, he worked on the design development for the UK prototype 3 MW turbine, before moving to Orkney to supervise its construction and commissioning. Later he moved to Wales to be site engineer for the construction and operation of Wind Energy Group's first wind farm at Cemmaes and he now works as a wind energy consultant.

Nick Jenkins was at the University of Manchester (UMIST) from 1992 to 2008. He then moved to Cardiff University where he is now Professor of Renewable Energy. His previous career had included 14 years industrial experience, of which five years were in developing countries. He is a Fellow of the IET, IEEE and Royal Academy of Engineering and for three years was the Shimizu Visiting Professor at Stanford University.

David Sharpe has worked in the aircraft industry for the British Aircraft Corporation as a structural engineer. From 1969 to 1995 he was a Senior Lecturer in aeronautical engineering at Kingston Polytechnic and at Queen Mary College, University of London. Between 1996 and 2003 he was at Loughborough University as a Senior Research Fellow at the Centre for Renewable Energy Systems Technology. David is a member of the Royal Aeronautical Society and was a member of the British Wind Energy Association at its inception. He has been active in wind turbine aerodynamics research since 1976.

Ervin Bossanyi: After graduating in theoretical physics and completing a PhD in energy economics at Cambridge University Ervin Bossanyi has been working in wind energy since 1978. He was a research fellow at Reading University and then Rutherford Appleton Laboratory before moving into industry in 1986 where he worked on advanced control methods for the Wind Energy Group. Since 1994 he has been with international consultants Garrad Hassan where he is a principal engineer.

Preface to Second Edition

The second edition of the *Wind Energy Handbook* seeks to reflect the evolution of design rules and the principal innovations in the technology that have taken place in the ten years since the first edition was published. A major new direction in wind energy development in this period has been the expansion offshore and so the opportunity has been taken to add a new chapter on offshore wind turbines and wind farms.

The offshore chapter begins with a survey of the present state of offshore wind farm development, before consideration of resource assessment and array losses. Then wave loading on support structures is examined in depth, including a summary of the combinations of wind and wave loading specified in the load cases of the IEC standard and descriptions of applicable wave theories. Linear (Airy) wave theory and Dean stream function theory are explained, together with their translation into wave loadings by means of Morison's equation. Diffraction and breaking wave theories are also covered.

Consideration of wave loading leads to a survey of the different types of support structure deployed to date. Monopile, gravity bases, jacket structures, tripods and tripiles are described in turn. In view of their popularity, monopiles are accorded the most space and, after an outline of the key design considerations, monopile fatigue analysis in the frequency domain is explained.

Another major cost element offshore is the undersea cable system needed to transmit power to land. This subject is considered in depth in the section on the power collection and transmission cable network. Machine reliability is also of much greater importance offshore, so developments in turbine condition monitoring and other means of increasing reliability are discussed. The chapter is completed by sections covering the assessment of environmental impacts, maintenance and access, and optimum machine size.

The existing chapters in the first edition have all been revised and brought up to date, with the addition of new material in some areas. The main changes are as follows:

Chapter 1: Introduction This chapter has been brought up to date and expanded.

Chapter 2: The wind resource Descriptions of the high frequency asymptotic behaviour of turbulence spectra and the Mann turbulence model have been added.

Chapters 3 and 4: Aerodynamics of horizontal axis wind turbines The contents of Chapters 3 and 4 of the first edition have been rearranged so that the fundamentals are covered in Chapter 3 and more advanced subjects are explored in Chapter 4. Some material on field-testing and performance measurement has been omitted to make space for a survey of wind turbine aerofoils and new sections on dynamic stall and computational fluid dynamics.

Chapter 5: Design loads for horizontal axis wind turbines The description of IEC load cases has been brought up to date and a new section on the extrapolation of extreme loads from simulations added. The size of the 'example' wind turbine has been doubled to 80 m, in order to be more representative of the current generation of turbines.

Chapter 6: Conceptual design of horizontal axis wind turbines The initial sections on choice of machine size, rating and number of blades have been substantially revised, making use of the NREL cost model. Variable speed operation is considered in greater depth. The section on tower stiffness has been expanded to compare tower excitation at rotational frequency and blade passing frequency.

Chapter 7: Component design New rules for designing towers against buckling are described and a section on foundation rotational stiffness has been added.

Chapter 8: The Controller Individual blade pitch control is examined in greater depth.

Chapter 9: Wind turbine installations and wind farms A survey of recent research on the impact of turbines on birds has been added.

Chapter 10: Electrical systems New sections covering (a) Grid Code requirements for the connection of large wind farms to transmission networks and (b) the impact of wind farms on generation systems have been added.

Acknowledgements for First Edition

A large number of individuals have assisted the authors in a variety of ways in the preparation of this work. In particular, however, we would like to thank David Infield for providing some of the content of Chapter 4, David Quarton for scrutinising and commenting on Chapter 5, Mark Hancock, Martin Ansell and Colin Anderson for supplying information and guidance on blade material properties reported in Chapter 7, and Ray Hicks for insights into gear design. Thanks are also due to Roger Haines and Steve Gilkes for illuminating discussions on yaw drive design and braking philosophy, respectively, and to James Shawler for assistance and discussions about Chapter 3.

We have made extensive use of ETSU and Risø publications and record our thanks to these organisations for making documents available to us free of charge and sanctioning the reproduction of some of the material therein.

While acknowledging the help we have received from the organisations and individuals referred to above, the responsibility for the work is ours alone, so corrections and/or constructive criticisms would be welcome.

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In addition, several individuals took on the onerous task of scrutinising sections of the draft text. The authors are particularly grateful to Tim Camp for examining the sections on design loading, on- and offshore, Colin Morgan for providing useful comments on the sections dealing with support structures and Graeme McCann for vetting sections on the extrapolation of extreme loads from simulations and monopile fatigue analysis in the frequency domain. Nevertheless, responsibility for any errors remains with the authors. (In this connection, thanks are due to those who have pointed out errors in the first edition).

Tony Burton would also like to record his thanks to Martin Kuhn and Wim Bierbooms for providing copies of their PhD theses – entitled respectively ‘Dynamics and design optimisation of offshore wind energy conversion systems’ and ‘Constrained stochastic simulation of wind gusts for wind turbine design’ – both of which proved invaluable in the preparation of this work.

List of Symbols

Note: This list is not exhaustive, and omits many symbols that are unique to particular chapters.

a	axial flow induction factor; flange projection beyond bolt centre
a'	tangential flow induction factor
a'_t	tangential flow induction factor at the blade tip
a_0	two-dimensional lift curve slope, $(dC_1/d\alpha)$
a_1	constant defining magnitude of structural damping
A, A_D	rotor swept area
A_∞, A_w	upstream and downstream stream-tube cross-sectional areas
A_c	Charnock's constant
b	face width of gear teeth; eccentricity of bolt to tower wall in bolted flange joint
b_r	unbiased estimator of β_r
B	Number of blades
c	blade chord; Weibull scale parameter; dispersion of distribution; flat plate half width; half of cylinder immersed width
c^*	half of cylinder immersed width at time t^*
$\hat{c}$	damping coefficient per unit length
c_i	generalised damping coefficient with respect to the ith mode
C	decay constant; wave celerity, L/T; constrained wave crest elevation
$C(\nu)$	Theodorsen's function, where ν is the reduced frequency: $C(\nu) = F(\nu) + iG(\nu)$
C_d	sectional drag coefficient
C_D	drag coefficient in Morison's equation
C_{DS}	steady flow drag coefficient in Morison's equation
C_f	sectional force coefficient (i.e. C_d or C_1 as appropriate)
C_1, C_L	sectional lift coefficient
C_M	inertia coefficient in Morison's equation
C_n^m	coefficient of a Kinner pressure distribution
C_p	pressure coefficient
C_P	power coefficient
C_Q	torque coefficient
C_T	thrust coefficient; total cost of wind turbine

C_{TB}	total cost of baseline wind turbine
C_x	coefficient of sectional blade element force normal to the rotor plane
C_y	coefficient of sectional blade element force parallel to the rotor plane
$C(\Delta r, n)$	coherence – i.e. normalised cross spectrum – for wind speed fluctuations at points separated by distance Δr measured in the across wind direction
$C_{jk}(n)$	coherence – i.e. normalised cross spectrum – for longitudinal wind speed fluctuations at points j and k
d	streamwise distance between vortex sheets in a wake; water depth
d_1	pitch diameter of pinion gear
d_{PL}	pitch diameter of planet gear
D	drag force; tower diameter; rotor diameter; flexural rigidity of plate; constrained wave trough elevation
E	energy capture, i.e. energy generated by turbine over defined time period; modulus of elasticity
$E\{\}$	time averaged value of expression within brackets
$E\left[H_s \mid \overline{U}\right]$	expected value of significant wave height conditional on a hub-height mean wind speed $\overline{U}$
f	tip loss factor; Coriolis parameter; wave frequency; source intensity
$f()$	probability density function
$f_1(t)$	support structure first mode hub displacement
$f_j(t)$	blade tip displacement in jth mode
$f_{in}(t)$	blade tip displacement in ith mode at the end of the nth time step
$f_J(t)$	blade j first mode tip displacement
f_p	wave frequency corresponding to peak spectral density
$f_{\mathrm{T}}(t)$	hub displacement for tower first mode
F	force; force per unit length
F_X	load in x (downwind) direction
F_Y	load in y direction
F_{t}	force between gear teeth at right angles to the line joining the gear centres
$F(\mu)$	function determining the radial distribution of induced velocity normal to the plane of the rotor
$F()$	cumulative probability distribution function
$F(x \mid U_k)$	cumulative probability distribution function for variable x conditional on $U = U_k$
g	acceleration due to gravity; vortex sheet strength; peak factor, defined as the number of standard deviations of a variable to be added to the mean to obtain the extreme value in a particular exposure period, for zero-up-crossing frequency, v
g_0	peak factor as above, but for zero upcrossing frequency n_0
G	geostrophic wind speed; shear modulus; gearbox ratio
$G(f)$	transfer function divided by dynamic magnification ratio
$G(t)$	t second gust factor
h	height of atmospheric boundary layer; duration of time step; thickness of thin-walled panel; maximum height of single gear tooth contact above critical root section
H	hub height; wave height; hub height above mean sea level

H_1	1 year extreme wave height
H_{50}	50 year extreme wave height
H_{jk}	elements of transformational matrix, **H**, used in wind simulation
$H_i(n)$	complex frequency response function for the ith mode
$H(f)$	frequency dependant transfer function
H_s	significant wave height
H_{s1}	1 year extreme significant wave height based on 3 hour reference period
H_{s50}	50 year extreme significant wave height based on 3 hour reference period
H_B	breaking wave height
I	turbulence intensity; second moment of area; moment of inertia; electrical current (shown in bold when complex)
I_B	blade inertia about root
I_0	ambient turbulence intensity
I_{15}	expected value of hub height turbulence intensity at reference mean wind speed of 15 m/s
I_+	added turbulence intensity
I_{++}	added turbulence intensity above hub height
I_R	inertia of rotor about horizontal axis in its plane
I_u	longitudinal turbulence intensity
I_v	lateral turbulence intensity
I_w	vertical turbulence intensity
I_{wake}	total wake turbulence intensity
j	$\sqrt{-1}$
k	shape parameter for Weibull function; shape parameter for GEV distribution; integer; reduced frequency, $(\omega c/2W)$; wave number, 2π/L; surface roughness
k_i	generalised stiffness with respect to the ith mode, defined as $m_i\omega_i^2$
k_1, k_2	marine conditions reference period conversion factors
K	constant on right hand side of Bernouilli equation
K_C	Keulegan-Carpenter number
K_P	power coefficient based on tip speed
K_{SMB}	size reduction factor accounting for the lack of correlation of wind fluctuations over structural element or elements
$K_{Sx}(n_1)$	size reduction factor accounting for the lack of correlation of wind fluctuations at resonant frequency over structural element or elements
$K_v()$	modified Bessel function of the second kind and order v
$K(\chi)$	function determining the induced velocity normal to the plane of a yawed rotor
L	length scale for turbulence (subscripts and superscripts according to context); lift force; wave length
L_u^x	integral length scale for the along wind turbulence component, u, measured in the longitudinal direction, x
m	mass per unit length, integer; depth below seabed of effective monopole fixity; inverse slope of log-log plot of S-N curve
m_i	generalised mass with respect to the ith mode
m_{T1}	generalised mass of tower, nacelle and rotor with respect to tower first mode
M	moment; integer; tower top mass
$\overline{M}$	mean bending moment

M_0	peak quasi-static mudline moment
$M_1(t)$	fluctuating cantilever root bending moment due to excitation of first mode
M_T	teeter moment
M_X	blade in-plane moment (i.e. moment causing bending in plane of rotation); tower side-to-side moment
M_Y	blade out-of-plane moment (i.e. moment causing bending out of plane of rotation); tower fore-aft moment
M_Z	blade torsional moment; tower torsional moment
M_{YS}	low-speed shaft moment about rotating axis perpendicular to axis of blade 1
M_{ZS}	low-speed shaft moment about rotating axis parallel to axis of blade 1
M_{YN}	moment exerted by low-speed shaft on nacelle about (horizontal) y-axis
M_{ZN}	moment exerted by low-speed shaft on nacelle about (vertical) z-axis
n	frequency (Hz); number of fatigue loading cycles; integer; distance measured normal to a surface
n_0	zero up-crossing frequency of quasistatic response
n_1	frequency (Hz) of 1st mode of vibration
N	number of blades; number of time steps per revolution; integer; design fatigue life in number of cycles for a given constant stress range
$N(r)$	centrifugal force
$N(S)$	number of fatigue cycles to failure at stress level S
p	static pressure
$p()$	probability density function
P	aerodynamic power; electrical real (active) power
$P_n^m()$	associated Legrendre polynomial of the first kind
$q(r, t)$	fluctuating aerodynamic lift per unit length
Q	rotor torque; electrical reactive power
Q_a	aerodynamic torque
$\dot{Q}$	rate of heat flow
$\overline{Q}$	mean aerodynamic lift per unit length
Q_D	dynamic factor defined as ratio of extreme moment to gust quasistatic moment
Q_g	load torque at generator
Q_L	loss torque
$Q_n^m()$	associated Legrendre polynomial of the second kind
$Q_1(t)$	generalised load, defined in relation to a cantilever blade by Equation (A5.13)
r	radius of blade element or point on blade; correlation coefficient between power and wind speed; radius of tubular tower; radius of monopile
r'	radius of point on blade
r_1, r_2	radii of points on blade or blades
R	blade tip radius; ratio of minimum to maximum stress in fatigue load cycle; electrical resistance
Re	Reynold's number
$R_u(n)$	normalised power spectral density, $n.S_u(n)/\sigma_u^2$, of longitudinal wind-speed fluctuations, u, at a fixed point
s	distance inboard from the blade tip; distance along the blade chord from the leading edge; separation between two points; Laplace operator; slip of induction machine
s_1	separation between two points measured in the along-wind direction