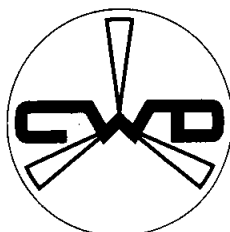


Introduction to Wind Energy

By E.H. Lysen

CWD 82-1
May 1983 (2nd. Edition)



CONSULTANCY SERVICES
WIND ENERGY
DEVELOPING COUNTRIES

P.O. BOX 85
3800 AB AMERSEFOORT
THE NETHERLANDS

PUBLICATION CWD 82-1

This publication has been prepared under the auspices of CWD, Consultancy Services Wind Energy Developing Countries.

CWD is a joint activity of:

- the Eindhoven University of Technology
- the Twente University of Technology
- DHV Consulting Engineers

CWD is financed by the Netherlands Programme for Development Cooperation.

CWD promotes the interest for wind energy in developing countries and provides professional advice and assistance to governments, institutes and private parties.

Until 1984 CWD had the name SWD, Steering Committee Wind Energy Developing Countries. Where the name SWD occurs in this report or in any other publication, it should be read as CWD

**COPYRIGHT © 1982
BY DEVELOPMENT COOPERATION INFORMATION DEPARTMENT**

All rights reserved, including the rights to reproduce this book or portions thereof in any form.
For information: CWD c/o DHV Raadgevend Ingenieursbureau BV, P.O. Box 85, 3800 AB Amersfoort The Netherlands.

Introduction to wind energy

**Basic and advanced introduction to wind energy
with emphasis on water pumping windmills**

**By:
E.H. Lysen**

May 1983

ACKNOWLEDGEMENT

Most of the material contained in this publication is based upon the work of the Wind Energy Group of the Eindhoven University of Technology, the Netherlands, guided by Paul T. Smulders. Part of the work has been carried out by graduate students in the University Wind Energy programme and a large part stems from the work of the staff employed by the programme for the Steering Committee Wind Energy Developing Countries (SWD), funded by the Netherlands Minister of Development Co-operation. The latter programme focuses on the application of wind energy for water pumping.

I have brought together the work of the following persons, mentioned in alphabetical order:

Jos Beurskens	:	aerodynamic theory
Peter van de Does	:	dynamic behaviour of piston pumps
Kees Heil	:	aerodynamic theory
Dirk Hengeveld	:	matching generators and rotors
Geert Hospers	:	air chambers, piston pumps, hinged vane safety system
Martin Houet	:	aerodynamic theory
Wim Jansen	:	rotor design
Gerard de Leede	:	starting behaviour rotor + pump
Erik Lysen	:	output prediction, coupling pumps and rotors, economics
Joop van Meel	:	pumps with leakhole, starting behaviour rotor, wind statistics
Adrie Kragten	:	piston pumps, hinged vane safety system, rotor design
Leo Paulissen	:	analysis wind regimes, matching generators and rotors
Rein Schermerhorn	:	forces on rotors
Paul Smulders	:	aerodynamic theory, rotor design, analysis wind regimes, output prediction
Jan Snoeij	:	valve behaviour in piston pumps

Marcel Stevens : Weibull analysis wind regimes, output
prediction
Niek van der Ven : acceleration effects in piston pumps
(Twente University)

A large number of students, not mentioned here, have made contributions to many of the subjects discussed.

Special thanks I am indebted to Ms. Ratrie and Ms. Varin of the Energy Technology Division, Asian Institute of Technology, Bangkok, who typed the first draft of this Introduction, and to Mrs. Riet Bedet, of the Wind Energy Group in Eindhoven, who has spent tiring hours before the screen, new for her, to get text and formulas on the floppy disk. Thanks also to Ms. Ruth Gruyters who has professionally redrawn my sketches and to Mr. Jan van Haaren for screening my English.

E.L.
Eindhoven
January 1982

The second edition

The second edition is identical to the first edition, except that some misleading definitions have been revised and typing errors have been corrected. Suggestions for further improvements are most welcome.

E.L.
Amersfoort
May 1983

CONTENTS	Page
Acknowledgement	5
List of symbols	10
1. INTRODUCTION	15
2. AVAILABLE POWER AND SITE SELECTION	16
2.1 Available wind power	16
2.2 Site selection	19
3. ANALYSIS WIND REGIMES	26
3.1 General	26
3.2 Time distribution	29
3.3 Frequency distribution	32
3.4 Mathematical representation of wind regimes (advanced)	36
4. ROTOR DESIGN	51
4.1 General	51
4.2 Power, torque and speed	51
4.3 Airfoils: lift and drag	56
4.4 The maximum power coefficient	61
4.5 Design of the rotor	65
4.6 Power from airfoils: the sailboat analogy (advanced)	74
4.7 Axial momentum theory (advanced)	77
4.8 Blade element theory (advanced)	85
4.9 Combination of momentum theory and blade element theory (advanced)	87
4.10 Tip losses (advanced)	90
4.11 Design for maximum power output (advanced)	92
4.12 Calculating the rotor characteristics (advanced)	96

5.	PUMPS	98
5.1	General	98
5.2	Piston pumps	101
5.3	Acceleration effects (advanced)	107
5.4	Valve behaviour (advanced)	117
5.5	Air chambers (advanced)	125
6.	COUPLING OF PUMP AND WIND ROTOR	140
6.1	Description and example	140
6.2	Mathematical description windmill output (advanced)	144
6.3	Starting behaviour (advanced)	149
6.4	Piston pumps with a leakhole (advanced)	154
6.5	Starting behaviour including leakhole (advanced)	162
6.6	Simplified leakhole theory	164
7.	GENERATORS	166
7.1	Synchronous machine (SM)	166
7.2	Asynchronous machine (AM)	168
7.3	Comparison of SM and AM	170
7.4	Commutator machine (CM)	173
7.5	Applications for wind energy	174
8.	COUPLING A GENERATOR TO A WIND ROTOR	175
8.1	Generator and wind rotor with known characteristics	175
8.2	Designing a rotor for a known variable speed generator	178
8.3	Calculation example	182
8.4	Mathematical description wind turbine output (advanced)	184
9.	MATCHING WINDMILLS TO WIND REGIMES: OUTPUT AND AVAILABILITY	190
9.1	Outline of the methods	190
9.2	Mathematical description of output and availability (advanced)	197

10.	ROTOR STRESS CALCULATIONS	210
10.1	General	210
10.2	Loads on a rotor blade (advanced)	212
10.3	Stresses in the rotor spoke at the hub (advanced)	223
10.4	Calculation of the combined stresses (advanced)	225
11.	SAFETY SYSTEMS	234
11.1	Survey of different safety systems	235
11.2	Hinged vane safety system (advanced)	237
12.	COSTS AND BENEFITS	261
12.1	General	261
12.2	Elementary economics	263
12.3	Costs of a water pumping windmill	272
12.4	Costs of a diesel powered ladder pump	275
12.5	Comparison of wind and diesel costs	278
13.	LITERATURE	286
14.	QUESTIONS	289
	APPENDICES A: Air density	297
	B: Gyroscopic effects (advanced)	301
	INDEX	309
	SWD Publications	311

LIST OF SYMBOLS*

a	axial induction (interference) factor	-
a'	tangential induction (interference) factor	-
A	area	m ²
b	span of wing (blade)	m
B	number of blades	-
c	exponent (section 8.4)	-
c	chord of blade	m
c	friction coefficient (section 5.5.4)	-
c	Weibull scale parameter	m/s
C	velocity in leak hole (section 6.4)	m/s
C _a	acceleration coefficient	-
C _d	sectional drag coefficient	-
C _D	blade drag coefficient	-
C _l	sectional lift coefficient	-
C _L	blade lift coefficient	-
C _N	normal force coefficient	-
C _P	power coefficient	-
C _Q	torque coefficient	-
C _T	thrust coefficient	-
d	distance	m
d	diameter leak hole	m
D	diameter	m
D	drag force	N
e	eccentricity rotor axis	m
e _{system}	reduced energy output of wind system	-
E	energy	J
f	friction factor	-
f	eccentricity rotor plane with respect to vertical axis of rotor head	m
f	probability density function	s/m
f	frequency	1/s
F	force	N
F	Prandtl's tip loss factor (section 4.10)	m

* Note: the symbols of chapter 12 are mentioned separately at the beginning of the chapter.

F	cumulative distribution function	-
F	function (section 11.2)	-
g	acceleration of gravity (9.8 m/s ²)	m/s ²
G	weight	N
G	approximation for gamma function (section 3.4.2)	-
h	distance centre of rotation of aerodynamic forces on main vane to vertical axis of rotor head (section 11.2)	m
H	lifting head	m
i	transmission ratio	-
i	distance (section 11.2)	m
I	mass moment of inertia	kg m ²
J	first moment of inertia	kg m
k	spring constant	N/m
k	Weibull shape factor	-
k _E	energy pattern factor	-
l	length	m
L	length	m
L	lift force	N
L	ratio λ_{\max}/λ_d (section 9.2.3)	-
m	mass	kg
M	moment	Nm
n	revolutions per second	1/s
N	normal force	N
p	pressure	N/m ²
p	number of pairs of poles (ch. 7)	N/m ²
P	power	W
q	flow	m ² /s
Q	torque	Nm
r	local radius	m
R	radius	m
Re	Reynolds number	-
s	standard deviation (discrete)	-
s	stroke	m
s	slip (section 7.2)	-

S	velocity duration function	-
t	time	s
T	length of period	s
T	dimensionless time (section 5.5.5)	-
T	thrust force	N
T	temperature	K
T	function (section 11.2)	K
u	component of wind velocity in x-direction	m/s
U	speed	m/s
v	component of wind velocity in y-direction	m/s
V	wind velocity	m/s
V_1, V_∞	undisturbed wind velocity	m/s
\bar{V}	average wind velocity	m/s
V_2	wind velocity far behind the rotor	m/s
w	component of wind velocity in z-direction	m/s
W	relative wind velocity	m/s
W	work	Nm
x	coordinate	m
x	relative radius (r/R)	-
x	reduced wind velocity (v/\bar{V})	-
y	coordinate	m
z	coordinate height	m
z_0	roughness height	m

α	angle of attack profile (or vane)	-
β	blade setting angle	-
β	damping coefficient (section 5.5.4)	-
γ	angle between actual position of main vane and its rest position	-
γ	exponent in gas law	-
Γ	circulation	m^2/s
$\Gamma(x)$	gamma function	-
δ	angle of yaw (rotor axis - wind direction)	-
ϵ	angle between hinge axis and vertical axis of rotor head (in plane of vertical axis and rotor axis)	-
η	efficiency	-
θ	blade position angle	-
V	volume	m^3
λ	tip speed ratio	-
λ_r	local speed ratio	-
μ	dynamic viscosity	Ns/m^2
μ	constant (section 5.4)	-
ν	kinematic viscosity	m^2/s
ξ	angle between auxiliary vane and rotor plane	-
π	3.14159265359	-
ρ	density	kg/m^3
σ	standard deviation	-
σ	tensile stress (ch. 10)	N/mm^2
σ	solidity ratio of a rotor	-
τ	time constant	-
τ	shearing stress (ch. 10)	N/mm^2
τ	tilting angle of rotor shaft	-
τ	availability (section 9.2.6)	-
ϕ	dimensionless flow (section 5.5.5)	-
ϕ	angle between relative wind direction (W) and rotor plane ($\phi = \alpha + \beta$)	-
ψ	phase angle (section 5.5.4)	-
ω	induced tangential angular wind velocity	$1/\text{s}$
Ω	angular velocity of rotor	$1/\text{s}$

INDICES

a	acceleration	p	pump piston
a	air, airchamber (5.5)	P	power
a	axial (ch. 10)	q	torque
a	auxiliary vane (11.2)	Q	torque
av	above valve (5.4)	r	radius (local)
ax	axial (ch. 4)	r	radial
b	blade, bending	r	rated
bv	below valve (5.4)	r	reference (2.2.1)
cl	closed (5.4)	r	rotor
cyl	cylinder	s	static
d	design value	s	stroke
d	delivery pipe (5.5)	s	sideways (11.2)
f	friction	s	suction pipe (5.5)
f	side force (11.2)	s	spoke
g	gap	st	starting
g	weight (gravity)	st	stationary
G	generator	t	thrust
G	weight	t	tangential
i	inertia	t	tensile
id	ideal	T	thrust
in	cut-in	tr	transmission
inst	instationary	tot	total
leak	leakhole	v	valve
max	maximum	v	vane
mech	mechanical	vol	volumetric
min	minimum	w	water
N	normal	w	wind
out	cut-out	y	yaw

* The combined indices of chapter 10 are explained at the beginning of chapter 10.

1. INTRODUCTION

This publication is the written result of three courses given at the Asian Institute of Technology in Bangkok, one in 1980 and two in 1981, funded by the Netherlands Minister of Development Co-operation.

It is based upon the information and experience contained in SWD publications, in the internal publications of the SWD participants (see the Acknowledgement), and in the open literature. Some subjects have never been published before, such as the behaviour of the hinged vane safety system, the dynamic behaviour of valves in piston pumps and the starting behaviour of windmills with piston pumps.

The texts have been written when the author was a member of the Wind Energy Group of the Eindhoven University of Technology, the Netherlands.

The reader is assumed to have a knowledge of physics and mathematics on an undergraduate level. The publication aims at practical applications such as analyzing wind regimes, designing wind rotors, calculating energy outputs etc., but also provides the mathematics behind these. Construction details of windmills will hardly be touched upon, however, as they are the subject of special SWD publications. Also a general introduction on the history of windmills and their different types and applications is omitted, because they can be found in many excellent books [1-4].

Nearly each chapter of this publication is divided into two parts, an introductory part and an advanced part, as indicated in the Contents.

The introduction parts together form a complete introductory course, which could be given separately. These parts at the same time prepare for the understanding of the advanced parts, presented in eight of the twelve chapters.