Introduction to Wind Energy

By E.H. Lysen

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Introduction to wind energy

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

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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 (Twente University) : acceleration effects in piston pumps

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

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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

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	diametre leak hole	m
D	diametre	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
$\overline{V}$	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 velocith ($V/\overline{V}$)	-
y	coordinate	m
z	coordinate height	m
z_o	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 vain and it 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	-
∇	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/s
Ω	angular velocity of rotor	1/s

INDICES

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